

Oil Spill Disaster Monitoring along Nigerian Coastline

Fatai O. A. EGBERONGBE, Peter C. NWILO and Olusegun T. BADEJO, Nigeria

Key words: oil spill, disaster, monitoring

SUMMARY

In 1956, Royal Dutch Shell discovered crude oil at Oloibiri, a village in the Niger Delta, and commercial production began in 1958. Today, there are 606 oil fields in the Niger Delta, of which 360 are on-shore and 246 offshore. Nigeria is now the largest oil producer in Africa and the sixth largest in the world, averaging 2.7 million barrels per day (bbl/d) in 2006. Nigeria's proven oil reserve is 35.2 billion barrels. Earnings from crude oil sales in Nigeria over the last 45 years is about \$600 billion.

Since the discovery of oil in Nigeria in 1956, the country has been suffering the negative environmental consequences of oil exploration and exploitation. Between 1976 and 2005, Nigeria recorded 9,107 oil spill incidents, which led to the spill of 3, 121, 909.8 barrels of oil. Several oil spill related laws and policies have been put in place to manage oil spill incidents in the country.

Physical, chemical, and biological processes that depend on the oil properties, hydrodynamics, meteorological and environmental conditions govern the transport and fate of spilled oil in water bodies. These processes include advection, surface spreading, evaporation, dissolution, sedimentation, emulsification, photo-oxidation, and biodegradation.

A new oil spill trajectory model has been developed. Appropriate wave driven current equation was coupled with that of wind drift current, ocean current, tidal current and longshore current to generate a new model for advecting oil spill on coastal waters. Existing oil fate models for calculating the rate of spreading and evaporation of oil were also included in this work to enable efficient tracking of oil spill on water.

The results from an hypothetical simulation from a point around OPL 250 located about 150km off the Nigerian coastline shows that the simulated oil spill for wet season reached the shore (around Penington River) after 104 hours (about 4.5 days). Also during the dry season, the results from the model indicate that the oil spill reached the shore (at the entrance of Benin River) after 162 hours (6.5 days).

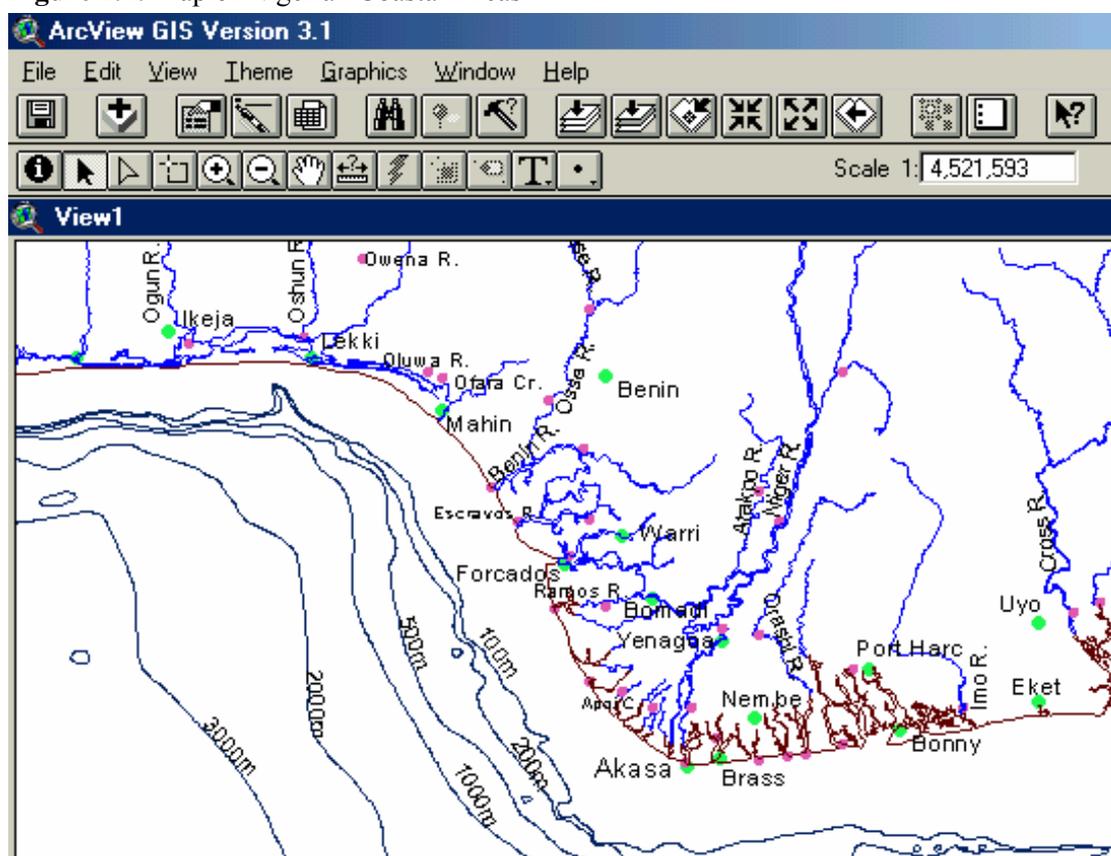
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1. INTRODUCTION

Nigeria is bordered to the North by the Republics of Niger and Chad, to the West by the Republic of Benin, to the East by the Republic of Cameroon and to the South by the Atlantic Ocean (Dublin Green et al, 1999). Nigeria has a coastline of approximately 853km facing the Atlantic Ocean. This coastline lies between latitude 4° 10' to 6° 20'N and longitude 2° 45' to 8° 35' E. The terrestrial portion of this zone is about 28,000 km² in area, while the surface area of the continental shelf is 46,300km².

Figure 1.1: Map of Nigerian Coastal Areas



The coastal area is low lying with heights of not more than 3.0 m above sea level and is generally covered by fresh water swamp, mangrove swamp, lagoonal marshes, tidal channels, beach ridges and sand bars (Dublin- Green *et al*, 1997). Nigeria's total land and water area is 923,768 sq km, with the area of the land being 910,768 sq km while that of water is 13,000 sq

km (CIA World Fact Book, 2005). The map of the Nigerian coastal areas is shown in Figure 1.1 above.

1.1 Climate of Nigeria's Coastal Areas

The Nigerian coastal zone experiences a tropical climate consisting of rainy season (April to November) and dry season (December to March). High temperatures and humidity as well as marked wet and dry seasons characterize the Nigerian climate. The coastal areas have an annual rainfall ranging between 1,500 and 4,000 mm (Kuruk, 2004).

Temperatures in the coastal areas are moderated by the cloud cover and by the generally damp air. However, mean monthly temperature vary between 24° C and 32° C throughout the year. The mean annual temperature for Port Harcourt is 26.8° C, for Warri, it is 26.6° C and for Akassa is 25.5° C. Mean monthly temperatures vary very little (about 2°) over the Nigerian coast.

The Nigerian coastal area experiences mainly the south westerlies which are onshore and confined generally to azimuths of 215°-266° with velocities of 2-5m/s. During the rainy season, wind speed exceeding 10m/s in the form of thunderstorms and line squalls are more persistent while during the dry season, offshore north eastly winds reach the coastline with less intensities.

1.2 Hydrology of Nigeria

The hydrology of Nigeria is dominated by two great river systems, the Niger-Benue and the Chad systems. With the exception of a few rivers that empty directly into the Atlantic Ocean, all other flowing waters ultimately find their way into the Chad basin or down the lower Niger to the sea. The two river systems are separated by a primary watershed extending northeast and north-west from the Bauchi Plateau which is the main source of their principal tributaries. North-west of the plateau lie the elevated, drift-covered plains of central Hausaland which is drained by numerous streams all flowing outwards to join the major tributaries (Kuruk, 2004).

1.3 Geology of Nigeria's Coast

The Nigerian coastal geology is basically sedimentary and is dominated by the geology of arcuate Niger delta. The Niger delta is composed of an overall classic sequence which reaches a maximum thickness of 9-12 kilometers (Ibe 1988). The Nigerian continental shelf is narrow in the west (less than 30km) but relatively broad off the Niger Delta and the eastern flank where it measures 45-80 km in width. The shelf is interrupted by several submarine canyons which include Avon, Mahin and Calabar Canyons

1.4 Geomorphological Units of Nigerian Coastal Areas

The Nigerian coast is composed of four distinct geomorphological units namely the Barrier-Lagoon complex; the Mud coast; the Arcuate Niger delta; and the Strand coast (Ibe 1988). The

geomorphology of the Lagos Lagoon is classified under the Barrier-Lagoon Complex which extends for about 250km from the Nigerian/Benin Republic border to Ajumo village. The Complex consists of narrow beach ridges which are aligned parallel to the coast. The beach sediments varied from medium to coarse grained sand.

1.5 Vegetation of Nigeria's Coastal Areas

The vegetation of the Nigerian coastal area is characterised by mangrove forests, brackish swamp forests and rain forests. The surrounding vegetation around the lagoon is largely mangrove, herbaceous and shrub plants dotted by raffia palm, Raffia sudanica, oil palm, Elaeis guineensis and few coconut palms Cocos nucifera. Palms and coconut trees dominate the beach ridges of the Badagry-Lagos-Lekki barrier lagoon complex. Mangroves dominate the vegetation of the Mahin Mud Beach. The white mangroves are found in Awoye and Molume areas.

The Niger Delta is characterised by extensive freshwater and mangrove swamps. The fresh water swamps consist of stilt rooted trees and shrubs. The main vegetation of the mangrove swamps of the Niger Delta is dominated by the red mangrove, which forms, more than ninety percent (90%) of the saline swamps. The white mangrove occurs scattered among the red mangroves and thrives in less water-logged place. Ferns, Nipa palm and herbs are found in areas where their salt content is not too high.

1.6 Oil Exploration And Exploitation

In 1956, Shell British Petroleum (now Royal Dutch Shell) discovered crude oil at Oloibiri, a village in the Niger Delta, and commercial production began in 1958. Today, there are 606 oil fields in the Niger Delta, of which 360 are on-shore and 246 offshore. These have been parceled out to the oil multinationals for extraction. Also, over 3,000 kilometers of pipeline lie across the landscape of the Delta, linking 275 flow stations to various export facilities (Adebanwi, 2001).

Nigeria is now the largest oil producer in Africa and the sixth largest in the world, averaging 2.7 million barrels per day (bbl/d) in 2006. The Nigerian government plans to increase oil production to 3 million bb/d before the end of 2006 and 4 million bbl/d in 2010. Figure 1.2 below shows the Crude oil production in Nigeria from 1980 to 2004.

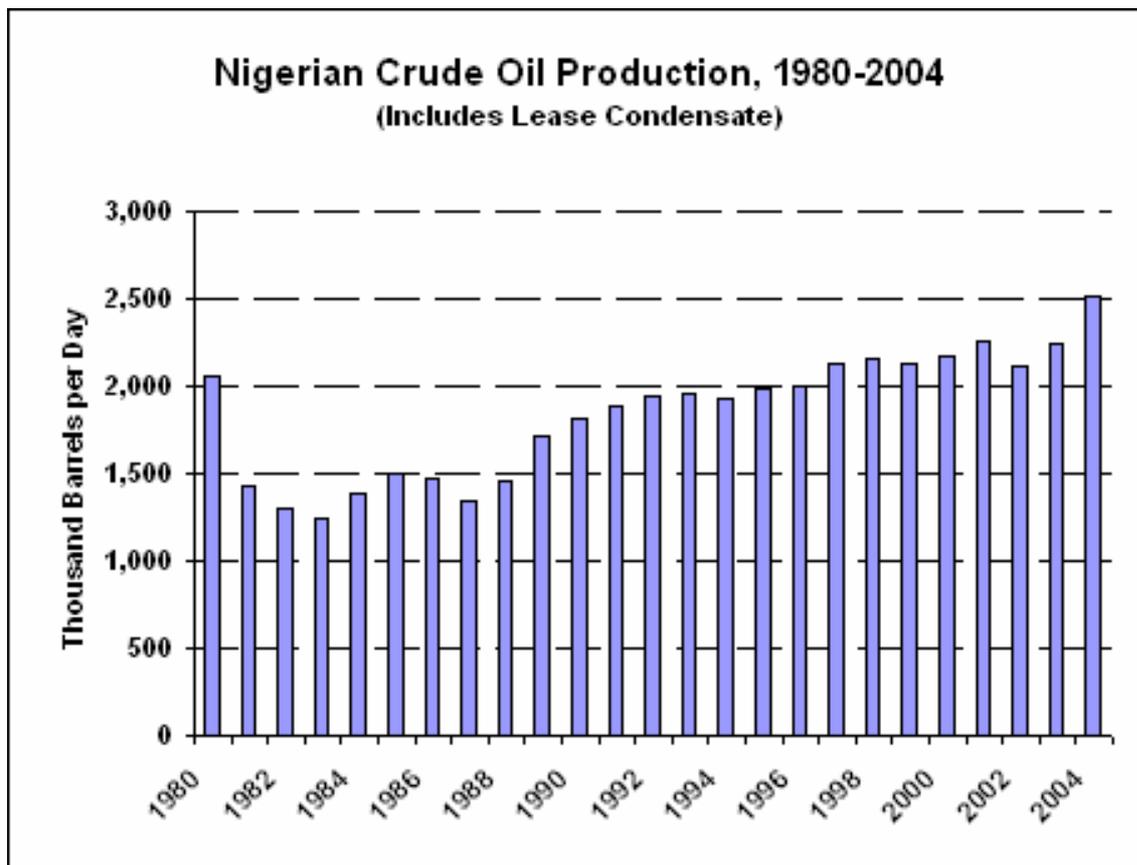


Figure 1.2: Nigerian Crude Oil Production

Earnings from crude sales in Nigeria over the last 45 years is about \$600 billion. Nigeria is also a major oil supplier to both Western Europe and the United States, with Asia and Latin America becoming increasingly important as well. In 2004, Nigerian crude exports to the United States averaged 1.1 bbl/d (Nigeria Country Analysis Brief, 2005).

Nigeria's economy is heavily dependent on earnings from the oil sector, which provides 20% of GDP, 95% of foreign exchange earnings, and about 65% of budgetary revenues (CIA World Fact Book, 2005). Nigeria has six export terminals including Forcados and Bonny (operated by Shell), Escravos and Pennington (ChevronTexaco), Qua Iboe (ExxonMobil), Brass (Agip), and Bonny Island LNG (Nigeria LNG). Shell's Bonny terminal is currently undergoing a \$600 million expansion and will export 1.5 million bbl/d after its completion in 2006. (Nigeria Country Analysis Brief, 2005)

1.6.1 Oil and Gas Reserves in Nigerian Coastal Areas

Oil and Gas Journal (2005) estimates Nigeria's proven oil reserved at 35.2 billion barrels. The Nigerian government plans to expand its proven reserves to 40 billion barrels by 2010. In

February 2005, Nigeria announced the award of five oil blocks in the Joint Development Zone (JDZ), shared by Nigeria and neighboring Sao Tome and Principe (STP). The JDZ reportedly holds reserves of 11 billion barrels and could potentially yield up to 3 million bbl/d in the next 2-3 years. Development is also occurring in the waters surrounding the JDZ. (*Nigeria Country Analysis Brief, 2005*)

According to Oil and Gas Journal (2005), Nigeria has an estimated 176 trillion cubic feet (Tcf) of proven natural gas reserves, giving the country one of the top ten natural gas endowments in the world and the largest endowment in Africa. In October 2004, Nigeria announced that its natural gas reserves could be as high as 660 Tcf. The government plans to raise earnings from natural gas exports to 50 percent of oil revenues by 2010.

1.6.2 Oil Spill Incidents in Nigeria

Thousands of barrels of oil have been spilt into the environment through our oil pipelines and tanks in the country. This spillage is as a result of our lack of regular maintenance of the pipelines and storage tanks. Sabotage is another major cause of oil spillage in the country.

Some major spills in the coastal zone are the GOCON's Escravos spill in 1978 of about 300,000 barrels and Texaco Funiwa-5 blow out in 1980 of about 400,000 barrels. Other oil spill incidents are the Jesse fire incident, which claimed about a thousand lives and the Idoho Oil Spill of January 1998, of about 40,000 barrels.

Table 1.1 below shows the record of oil spill incidents in the country from 1976 to 2005. The record below indicates that between 1976 and 2005, Nigeria recorded 9,107 oil spill incidents, which led to the spill of 3, 121, 909.8 barrels of oil. From the record below, we have the quantity of oil spill recovered for 1976 to 1996. The amount of oil spilled for this period is 2, 413, 604 barrels while 550, 232.9 barrels representing 22.80 percentage of the oil spilled was recovered.

The highest number of oil spill incidents occurred in 2000 with 637 oil spill incidents representing 6.99% of oil spill incidents between 1976 and 2005. A total spill of 84,071.91barrels, representing 2.69% of oil spilled between 1976 to 2005 was recorded for 2000. The amount of oil recovered for 2000 is not available.

The lowest number of oil spill incidents was recorded in 1977. The number of the oil spill incidents is 104 for 1977. This amount is 1.14% of the number of oil spill incidents from 1976 to 2005. The amount of oil spilled in 1977 is 32, 879 barrels, representing 1.05% of oil spilled between 1976 and 2005. The amount of oil spill recovered for the year is 1,703.01barrels which is just 5.18% of the amount spilled.

The heaviest oil spill occurred in 1979. A total of 157 incidents resulting in the spill of 694,170 barrels were spilled into the environment. The spills for 1979 represents 22.24% of oil spilled between 1976 and 2005. The amount of oil spilled recovered in 1979 is 63,481.20, representing 9.14% of oil spilled.

The smallest amount of oil spilled between 1976 and 2005 was recorded in 1989. In that year, 195 oil spill incidents which is 2.14% of the total oil spill incidents from 1976 to 2005 led to the spill of 7,628.16 barrels of oil. The amount spilled is a mere 0.24% of all the oil spilled between 1976 and 2005. The amount of oil recovered in 1989 is 2,153barrels, which represent 28.22% of the oil spilled in 1989.

Table 1.1: Record of Oil Spill Incidents in Nigeria

S/N	YR	NO. OF OIL SPILL	(%) OF NO. OF OIL SPILLED	QUANTITY OF OIL SPILLED (BARRELS)	(%) OF QUANTITY OF OIL SPILLED	QUANTITY RECOVERED (BARRELS)	PERCENTAGE (%) OF QUANTITY RECOVERED
1.	1976	128	1.41	26,157.00	0.84	7,135.00	27.28
2.	1977	104	1.14	32,879.00	1.05	1,703.01	5.18
3.	1978	154	1.69	489,294.00	15.67	391,445.00	80.00
4.	1979	157	1.72	694,170.00	22.24	63,481.20	9.14
5.	1980	241	2.65	600,511.00	19.24	42,416.83	7.06
6.	1981	238	2.61	42,722.00	1.37	5,470.20	12.80
7.	1982	252	2.77	42,841.00	1.37	2,171.40	5.07
8.	1983	173	1.90	48,351.30	1.55	6,355.90	13.15
9.	1984	151	1.66	40,209.00	1.29	1,644.80	4.09
10.	1985	187	2.05	11,876.60	0.38	1,719.30	14.48
11.	1986	155	1.70	12,905.00	0.41	552	4.28
12.	1987	129	1.42	31,866.00	1.02	6,109.00	19.17
13.	1988	208	2.28	9,172.00	0.29	1,955.00	21.31
14.	1989	195	2.14	7,628.16	0.24	2,153.00	28.22
15.	1990	160	1.76	14,940.82	0.48	2,092.55	14.01
16.	1991	201	2.21	106,827.98	3.42	2,785.96	2.61
17.	1992	378	4.15	51,187.96	1.64	1,476.70	2.88
18.	1993	428	4.70	9,752.22	0.31	2,937.08	30.12
19.	1994	515	5.65	30,282.67	0.97	2,335.93	7.71
20.	1995	417	4.58	63,677.17	2.04	3,110.02	4.88
21.	1996	430	4.72	46,353.12	1.48	1,183.02	2.55
22.	1997	339	3.72	81,727.85	2.62		
23.	1998	399	4.38	99,885.35	3.20		
24.	1999	225	2.47	16,903.96	0.54		
25.	2000	637	6.99	84,071.91	2.69		
26.	2001	412	4.52	120,976.16	3.88		
27.	2002	446	4.90	241,617.55	7.74		
28.	2003	609	6.69	35,284.43	1.13		
29.	2004	543	5.96	17,104.00	0.55		
30.	2005	496	5.45	10,734.59	0.34		
31.	Total	9,107		3,121,909.8		550,232.9	22.80

Modified After Department of Petroleum Resources

1.6.3 Oil Spill Disaster Management

The Federal Government, oil companies and non-governmental agencies have made several efforts to manage oil spill disaster along our coastline. The following efforts have been taken to manage oil spill incidents within and outside the country:

1. Enactment of the Oil Pollution Act of 1990.
2. Establishment of the National Oil Spill Detection and Response Agency (NOSDRA).
3. Establishment of the Niger Delta Development Commission (NDDC)
4. Enactment of Petroleum Related Laws and Regulations.
5. Promulgation of the Environmental Impact Assessment (EIA) decree No 86 of 1992.
6. Establishment of Federal and State agencies like Department of Petroleum Resources (DPR), Federal Ministry of Environment and State Ministries of Environment to deal with the problems of oil spill in Nigeria.
7. Formation of the Clean Nigeria Associates (C.N.A.) in November 1981 and other Non Governmental Agencies to combat spills of liquid hydrocarbons.
8. Deployment of Oil Trajectory and Fate Models for Oil Spill Disaster Monitoring
9. Removal and Treatment of Oil Spill by Natural Means and Mechanical Systems.
10. Launching of the Nigerian Sat 1 Satellite for Oil Spill Disaster Monitoring
11. Donation of Vessels by United States for Coastal Monitoring
12. Creation of Regional Spill Response Centres Along Coastlines
13. Creation of Oil Spill Sensitivity Index Maps in a GIS Environment.

2. TRANSPORTS AND FATE OF OIL SPILL

The transport and fate of spilled oil in water bodies are governed by physical, chemical, and biological processes that depend on the oil properties, hydrodynamics, meteorological and environmental conditions. These processes include advection, turbulent diffusion, surface spreading, evaporation, dissolution, emulsification, hydrolysis, photo-oxidation, biodegradation and particulation. When liquid oil is spilled on the sea surface, it spreads to form a thin film – an oil slick. The movement of the slick is governed by the advection and turbulent diffusion due to current and wind action. The slick spreads over the water surface due to a balance between gravitational, inertial, viscous and interfacial tension forces, while composition of the oil changes from the initial time of the spill. Light (low molecular weight) fractions evaporate, water-soluble components dissolve in the water column, and immiscible components become emulsified and dispersed in the water column as small droplets (Tkalic *et al*, 2003).

The formation of oil-in-water or water-in-oil emulsion depends upon turbulence, but usually occurs within days after the initial spill. It forms thick pancakes on the water and intractable sticky masses if it comes ashore. After a long time, this mousse may disintegrate into lumps of tar. Heavy oil fractions may attach to suspended sediments and be deposited to the seabed, where the bacterial degradation is much slower. Tar balls and mousse present a small surface area compared with their volume and degrade extremely slowly for this reason. Given enough time, the combined actions of weathering and biodegradation can eliminate most of the spilled oil. Unfortunately, nature does not always have enough time. The result is that oil may wash up on beaches or into biologically sensitive tidal

2.1 Oil Trajectory and Fate Models for Oil Spill Disaster Monitoring

Oil spill simulation model is used in oil response and contingency planning and as a tool in oil fate and impact assessment (Rossouw, 1998). In the event of an oil spill taking place, predictions of the slick can be supplied, provided that the necessary meteorological information is available (Rossouw, 1998).

Two approaches for computing oil spills trajectories are commonly encountered in the literature; Lagrangian models and Eulerian models. The Lagrangian models consist basically in representing the oil slick by an ensemble of a large number of small parcels which are advected by a velocity which results from a combination of the action of winds and currents. Then, the slick is divided into pie shaped segments or strips, depending if the form of the slick is nearly circular or elongated. Fay (1969) spreading formulas are then applied to each segment. For the Eulerian approach, two model are usually encountered, those based on the mass and momentum equations applied to the oil slick (Hess and Kerr (1979), Benqué et. al.(1982)), and those based on a convection-diffusion equation (Venkatesh (1988) among others), in which the diffusive part of the equation represents the spreading of oil by itself and the convective terms represents the advection of oil by currents and winds (Paladino and Maliska, 2000).

It is common practice to use Eulerian coordinates for solution of the partial differential equations in environmental hydraulics, in contrast to the tracking of the oil slick drifting that traditionally employs the Lagrangian approach. The Eulerian method appears to be used more frequently in future, because of the increasing need to couple the pollutant transport and chemical kinetics equations with (Eulerian) hydrodynamic models (Tkalich et al, 2003).

Many models have been developed to predict the motion of marine oil spills. In these models the external inputs for each time step include factors such as:

- i. Amount of oil spilled.
- ii. Type of oil spilled.
- iii. Location of oil spill source.
- iv. Wind magnitude and direction at each location.
- v. Current magnitude and direction at each location.

Given these data, the model can predict future world states, that is the distribution of oil on water at each time step (Jungfun & Jan, 1995).

There are few models available for managing oil spill incidents. Some of these models are developed abroad whereas a handful of them are developed locally. The major features of these models are:

- to predict the weathering of spilled oil.
- to model the sub-surface transport of spilled oil.
- to predict the probability of various areas being imparted by a spill from a given site.
- to asses the vulnerability of sites to oiling
- to model the effects of different oil clean-up scenarios.
- to perform risk assessments for the important resources.

- to assist in search and rescue operations.

Some of the software developed and in use for oil spill management are those developed by Hang et al (1989), Kung et al (1997), OILMAP, SIMAP, Coastal Zone Oil Spill model (COZOIL), Computer Model at S.L. Ross, Canada, Multiphase Oil Spill Model (MOSM), and Nigerian Oil Spill Model (NOSM).

The physical, chemical, and biological processes governing the transport and fate of oil spill are described below. Advection is the mechanism for transporting oil while the fate of oil spill is governed by spreading, evaporation, dissolution, entrainment, emulsification, biodegradation, photosynthesis, sedimentation and shoreline deposition.

2.2 Advection

Advection is the main mechanism that governs the drifting of suspended oil and surface oil slick. The advection of suspended oil is the movement of oil droplets entrained in the water column due to the water current (Reddy and Brunet, 1997). Some models include two mechanisms to advect or move the oil; these mechanisms are wind drift and currents. Some of these models specify a fixed percentage of the wind speed directly downwind for advection of oil on water.

2.3 Spreading

Spreading determines the area extent of the surface oil, which in turn affects the weathering of the oil. Spreading results from turbulent diffusion and the balance of gravity, inertia, viscosity and surface tension forces. In most models, Fay's spreading theory of 1971 is used. In Fay's theory oil spill is considered to pass through three phases. In the first phase, only gravity and inertial forces are important. In the second phase, the gravity and viscous forces dominate. The last phase is governed by the balance between surface tension and viscous forces. To apply this theory, the geometry for the oil slick is simplified into either one-dimensional or radial form. The criteria to determine the geometry of the oil slick is through the calculation of the aspect ratio. When the Aspect Ratio is less than 3, the radial spreading will be used. Formulas for spreading laws and rates of these two forms are given by the model.

2.4 Evaporation

Evaporation can be the largest contribution to oil weather removal, and depends on the type of oil, spill area, oil slick thickness, vapour pressure and mass transport coefficient. These in turn are composition of the oil, wind speed and temperature. Mackay Evaporative Exposure formula developed by (Mackay, 1980) is mostly used to calculate the evaporate rate of the oil.

2.5 Dissolution

This is the process in which soluble hydrocarbons enter the water column from the surface slick or entrained oil droplets. Dissolution accounts for much less of the mass balance than evaporation, except perhaps under ice. NOSM uses the Mackay and Leinonen algorithm for dissolution of oil. The method of (Cohen *et al*, 1980) and (Huang and Montastero, 1982) is used by (Hang et al, 1989).

2.6 Entrainment

This is a physical process in which oil particles are transported from the sea surface into the water column due to breaking waves. The entrained oil is broken down into droplets of varying sizes which spread and diffuse into water column. Entrained oil is subject to enhanced dissolution and biodegradation. Entrainment is greater during periods of higher wave energy. The Mackay expression is used by NOSM.

OILMAP modeled entrainment or natural dispersion by using Delvigne and Sweeney's (1988) formulation. The entrainment coefficient is a strong function of oil viscosity and is based on a curve fit to data given in Delvigne and Hulsen (1994). The breaking wave induced turbulent energy is expressed in terms of the root mean square wave height, which is estimated from the wind speed and fetch. The fraction of the sea surface impacted by breaking waves is dependent on the wind speed and wave period. In the absence of breaking waves (wind speeds less than 5m/sec) the fraction of sea surface impacted becomes zero and no entrainment is predicted.

Two options are available in COZOIL for simulating entrainment: one developed by Mackay *et al.* (1980a,b) and a second developed by Audunson (1979) and modified by Spaulding *et al.* (1982). The Mackay *et al.* (1980a,b) algorithm gives a mass transfer rate as a function of wind speed, oil viscosity, slick thickness, and the oil-water interfacial tension. The modified Audunson entrainment algorithm predicts a mass transfer rate based on the wind speed and the age of the oil.

2.7 Emulsification

This is the process by which water is mixed with oil, forming a "chocolate mousse" type compound that dramatically increases the oil/water mixture volume and increases viscosity. Formation of water-in-oil emulsions depends on oil composition and sea state. The emulsified oil can contain as much as 80% water, with water droplets dispersed within a continuous phase of oil. NOSM, OILMAP and COZOIL formulation on emulsification are based on a function of evaporative losses and changes in water content, which is based on Mackay et al (1980,1982).

2.8 Biodegradation

This is slow oil loss due to the ingesting and metabolizing of oil by various marine organisms. The amount of oil that can be biodegraded ranges from 11% to 90%. The variability is due to the variations in organisms for different locations, and the variation in oil components. NOSM

includes a first order decay process in which the rate of oil biodegraded is proportional to the initial mass and an empirical decay coefficient.

2.9 Photosynthesis

This is the decay of oil through photon excitement of the oil. Typically it is not an important process but can be included in oil trajectory and fate models.

2.10 Sedimentation

This process occurs when the specific gravity of oil increases over that of sea water. Several processes can cause this to occur, including weathering (evaporation, dissolution and emulsification), zooplankton ingestion, adhesion or sorption onto suspended particles, or interaction with the shoreline. Sedimentation is usually not important for mass balance calculations unless the concentration of suspended matter is high (>100mg/l). NOSM can model sedimentation as a “constant-rate” process.

The oil sedimentation algorithm by OILMAP is described in French et al (1994), ASA(1996) and Kirstein et al (1985). The rate of change of the volume of oiled sediments is expressed in terms of the product of the oil concentration, the suspended sediment concentration and an empirical reaction rate constant. If suspended particulate concentrations are below 100mg/l, no sedimentation occurs. Suspended sediment concentrates above 100mg/l are typical of highly turbid riverine and coastal waters and rarely occurs in shelf or oceanic flows. The settling velocity of the oil sediment is estimated using a modified Stokes law, which is dependent on the oil-sediment droplet size and density.

2.11 Shoreline Deposition

Oil shoreline interaction formulation by OILMAP is a model based on a simplified version of Reed et al (1989) which formulates the process in terms of a shore type dependent holding capacity and exponential removal rate. The holding capacity and removal rates are also dependent on oil viscosity. The shoreline is specified in terms of eleven separate type classes: rocky, wave cut platforms, four classes of beach (fine and coarse sand, mixed sand and gravel, gravel, cobble),tidal flats, sheltered coastal areas (rocky, tidal flat, marsh), and glaciers.

The fate of spilled oil that reaches the shoreline depends on characteristics of the oil, the type of shoreline, and the energy environment. Even when beached, oil will continue to weather. However, several additional processes become important: reflation, penetration into the substrate, and retention/transport in the beach-groundwater system. Erosion of oiled substrate from the beach may also occur.

The amount of oil which can be deposited onshore is a function of the area of the shore exposed to tide and wave action. COZOIL defines a beach width and angle (slope) for each type of shoreline which is then used in the calculation of exposed area.

NOSM simulates the shoreline deposition through an exponential decay function. The movement of oil slick in the model actually represents the movement of the centroid of the slick.

3. NEW OIL SPILL MODEL

We developed a new oil spill trajectory mathematical model capable of simulating oil transport along our coastal waters. In developing this new mathematical model, we considered the major factors responsible for transporting and advecting oil on water. The assumption made in our work is that oil will not mix with water, and that the density of oil spill is less than that of water, thus the oil spill will move on water and not sink. The work is also limited to oil spill on open coastal water or deep sea. We made no attempt to model the movement of oil spill on land or on swamps.

Advection is the main mechanism that governs the transportation of suspended and surface oil slick. The combined effects of the following factors advect oil on water:

- Wind drift current
- Waves
- Tides
- Ocean Current
- Longshore Current

The advection factors used in the model are described in the following subsections.

3.1 Wind Drift Current

The equation for the wind drift current is based on hyperbolic equations given by Officer (1976). The direction of the wind drift current is the sum of the wind direction and a deflection angle. The deflection angle of the wind drift current depends on latitude (Buranapratheprat and Tanjaaitrong, 2000).

3.2 Eulerian Surface Waves Drift

Sobey and Barker (1996) gave reliable estimates of surface kinematics. Higher order theory for Stokes waves predicts that the water particle subject to uniform periodic waves will be transported in the direction of the wave advance. Since the water particle speed (u) given by Stokes is the same as the horizontal water particle speed (u), Stokes water particle speed was integrated into the Eulerian surface wave drift velocity equation given by Sobey and Barker (1996) to get the speed of the Eulerian surface wave.

3.3 Tides

The tidal amplitude and phase for this work is based on the results of Schwiderski's global ocean tidal model and contained in Splaudling et al (1987). The tidal amplitudes and tides were input data into the equations for the speed of tide given by Nelkon and Parker (1982).

In a tide wave the horizontal motion, i.e. the particle velocity, is called the *tidal stream*. The vertical tide is said to *rise* and *fall*, and the tidal stream is said to *flood* and *ebb*. If the tide is progressive, the flood direction is that of the wave propagation. If the tide is a standing wave, the flood direction is inland or toward the coast (Canadian Hydrographic Service, 2005).

3.4 Ocean Currents

The ocean currents affecting the Nigerian coastal area include the following:

- Surface eastward flowing Guinea Current.
- Subsurface westward and northward flowing Benguela Current.
- Easterly flowing surface North Equatorial Counter Current.

Reddy and Brunnet (1997) gave the ocean current responsible for moving oil as 100 percent of the speed of the ocean current. During the wet season, the Guinea Current and the Easterly Flowing North Equatorial Counter Current are responsible for moving oil spill. The Guinea Current has speeds of 30cm s^{-1} and touches the sea bed at depths shallower than 50m. From time to time, the Guinea Current reverses its easterly flow. The reversal is believed to be due to effects of the Benguela Current. The mean eastward velocity for the NECC is 15 cm s^{-1} . This increases to speeds of more than 30 cm s^{-1} in the Guinea Current (Arnault, 1987). The greatest flow for the NECC occurs in the boreal summer with eastward speeds of up to 29 cm s^{-1} , which are reduced during the spring. There is a reversal of a majority of the current's flow in the western part of the basin during the early months of the year (Arnault, 1987).

During the Dry season, the Benguela current moves the oil spill. Shannon (1985) gathered all available information about surface speed from previous studies and calculated the mean speed of the Benguela Current to be 17 cm s^{-1} . (Wedepohl et al. 2000) found that the mean speeds of the current vary from $<11\text{ cm s}^{-1}$ to a maximum of 23 cm s^{-1} .

3.5 Longshore Currents

The longshore current speed for the work is based on Ibe and Antia, (1983). The longshore current direction for the model is based on Dublin Green et al (1997). Three main longshore drift directions along the Nigerian Coastline were specified by Dublin Green et al (1997). These directions are:

- The west-east littoral drift along the western coastline.
- The littoral drift off the north western flank of the Niger Delta.
- The west-east littoral drift between Akasa point and the Calabar estuary.

3.6 New Oil Spill Advection Model

The vector sums of the speed and directions of wind drift current, Eulerian surface wave drift, tides, ocean current and longshore current considered above will move the oil along our coastal waters.

These vector sums is the model's advection speed and direction, and are given by the equations below.

$$S_{NM} = \sqrt{(S_{WDC} \cos \theta_{WDC} + S_{SWD} \cos \theta_{SWD} + S_{TIDE} \cos \theta_{TIDE} + S_{OC} \cos \theta_{OC} + S_{LC} \cos \theta_{LC})^2 + (S_{WDC} \sin \theta_{WDC} + S_{SWD} \sin \theta_{SWD} + S_{TIDE} \sin \theta_{TIDE} + S_{OC} \sin \theta_{OC} + S_{LC} \sin \theta_{LC})^2} \quad \dots\dots\dots 3.1$$

$$\theta_{NM} = \tan^{-1} \frac{(S_{WDC} \sin \theta_{WDC} + S_{SWD} \sin \theta_{SWD} + S_{TIDE} \sin \theta_{TIDE} + S_{OC} \sin \theta_{OC} + S_{LC} \sin \theta_{LC})}{(S_{WDC} \cos \theta_{WDC} + S_{SWD} \cos \theta_{SWD} + S_{TIDE} \cos \theta_{TIDE} + S_{OC} \cos \theta_{OC} + S_{LC} \cos \theta_{LC})} \quad \dots\dots\dots 3.2$$

Where

- S_{WDC} = Speed of wind drift current
- θ_{WDC} = Direction of wind drift current
- S_{SWD} = Speed of Eulerian surface wave drift current
- θ_{SWD} = Direction of Eulerian surface wave drift current
- S_{TIDE} = Speed of tide
- θ_{TIDE} = Direction of tide.
- S_{OC} = Speed of ocean current.
- θ_{OC} = Direction of ocean current.
- S_{LC} = Speed of longshore current
- θ_{LC} = Direction of longshore current

In addition to the new oil spill advection model developed, we also looked into existing equations governing the fate of oil on water. We incorporated equations for the rate of spreading and evaporation of oil spill on water to our model. These equations are the most important factors in the determination of the fate of oil spill. Fay's (1971) spreading theory is used in the model. In the model, oil spill is assumed to spread radially under steady gravity and viscous forces, thus Fay's radial spreading formula for gravity and inertial forces is used. The formula developed by Mackay (1980) is used to calculate the evaporate rate of oil in the model.

The new trajectory model and the existing fate model was written in the Visual Basic Environment (Windows based). This was done so as to make the model user friendly, by making use of its powerful graphical user interface. Programming in the visual basic environment also enables us to link the model with a base map of the Nigerian coastal areas in a MapInfo GIS environment.

3.7 Study Area and Hypothetical Simulations of Oil Spill Position with the Model

An hypothetical spill site around OPL 250 located about 150km off the Nigerian coastline was chosen as the study area. The actual spill position is longitude 4° 30' 46.20" E and latitude 4° 25' 39.80" N.

Simulations were made for wet and dry seasons for the study area above. The simulations for the wet and dry seasons were done in four phases for each season. For phase one, simulations were made from the spill point up to a point around the 100m isobath. In phase two, simulations were

made from the point around the 100m isobath to a point about 20km to the coastline. Simulations for phase three were made from the point about 20km to the coastline up to another point about 10km to the coastline. Simulations for the last phase were made from the point about 10km to the coastline up to the coastline. The reason for making the simulations in four phases is that the effect of tides is negligible for the deep sea, while the tidal effect increases as one moves closer to the coastline. We have to vary the amplitudes and phases of tides along the coastal waters.

The simulated oil spill points for all the four phases for the wet season were plotted in MapInfo GIS software which is linked with the model in Visual Basic environment. The Oil Spill Trajectory for the wet season is shown in Figure 3.1 below.

The result of the simulation for wet season shows that the oil spill moves slower in deep sea and faster between the distances of 10km to 20km from the shoreline. The reason for this is that in the deep sea, there is no tidal effect while the tidal effect is prevalent in the 10km to 20km region. Also, the net effect of the longshore current and tides increased the speed of the oil spill near the shoreline.

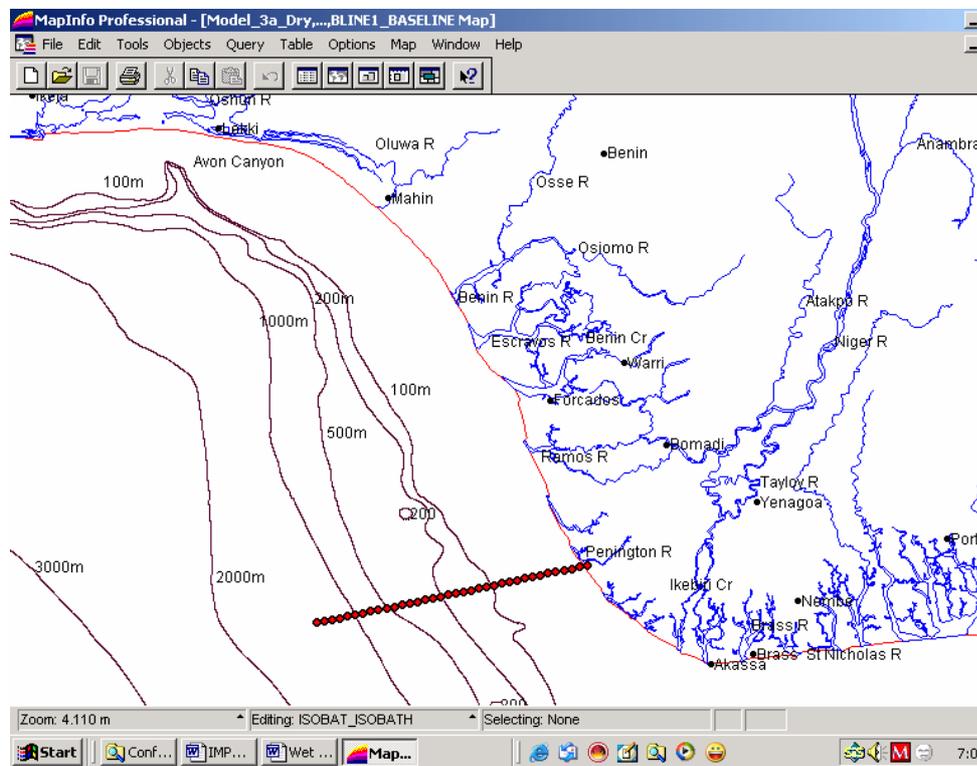


Figure 3.1: Oil Spill Trajectory for Wet Season on Nigerian Coastal Waters

The simulated oil spill for wet season reached the shore (around Penington River) after 104hours (about 4.5 days). The oil spill will continue to move along the shoreline towards Escravos (i.e. in the direction of the longshore current). When the tide is high, the oil spill will move into the coastal lands and negatively impact the ecosystem.

By the end of the 104 hours a total of 94,525.660barrels of oil would have evaporated. This amount represents 16.88% of the 560,000 barrels of oil spilt. In addition the Slick area at the end of the 104hours would be 1782.058km².

The simulated oil spill points for all the four phases for the dry season were plotted in MapInfo GIS software which is linked with the model in Visual Basic environment. The Oil Spill Trajectory for the dry season is shown in Figure 3.2 below.

The result of the simulation for dry season shows that the oil spill moves also moves slower in deep sea and faster between the distance of 10km to 20km from the shore line during the dry season. The reason for this is that in the deep sea, there is no tidal effect while the tidal effect is prevalent in the 10km to 20km boundary. Also, the net effect of the longshore current and tides increased the speed of the oil spill near the shoreline.

Tides and ocean currents are also the major factors responsible for oil spill movement along our coastline during the dry season. For the study location above, the magnitude of effective current velocity and directions remained the same throughout the four phases. The magnitudes of these are .17m/s and 0° respectively. Oil spill moves slower during the dry season. The reason for this is that the magnitude of the ocean current is lesser during the dry season.

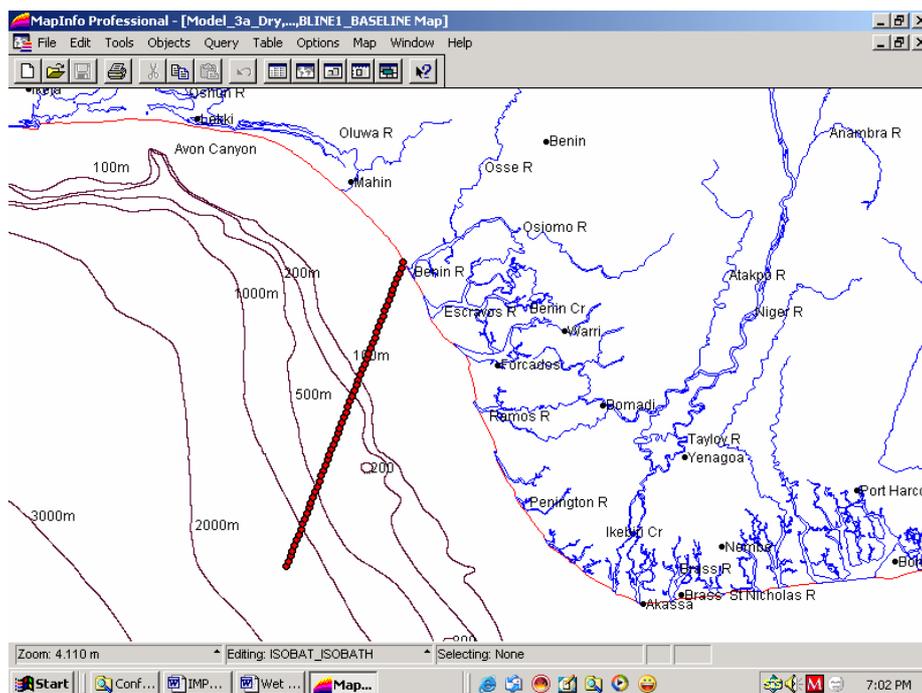


Figure 3.2: Oil Spill Trajectory for Dry Season on Nigerian Coastal Waters

Wind drift current and waves are also secondary factors for moving oil spill during the dry season. The wind drift current remained constant for the four phases. The wind drift current is about 2.% of the wind speed during the dry season. The wave velocity increases as one moves towards the shoreline. The magnitude of the wave velocity is lower than that of the wind drift in the first three phases, but higher than that of the wind drift current in the fourth phase. The effect

of waves is negligible in deep sea (1000m+) but cannot be dispensed with in shallow sea or near the coastline. The oil spill trajectory for the dry season is shown in Figure 4.1.

The results from the model for dry season indicate that the oil spill reached the shore (at the entrance of Benin River) after 162hours (6.5days). The oil spill would then move towards Forcados (i.e. in the direction of the longshore current) around where its flow would be affected by the longshore current coming from Penington end. The oil spill would be stationary at this point, and move into the coastlands during high waters.

By the end of the 162 hours a total of 147241.894barrels of oil would have evaporated. This amount represents 26.293% of the 560,000 barrels of oil spilt. In addition the slick area at the end of the 162hours would be 1628.440km².

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

In 1956, Royal Dutch Shell discovered crude oil at Oloibiri, a village in the Niger Delta, and commercial production began in 1958. Today, there are 606 oil fields in the Niger Delta, of which 360 are on-shore and 246 offshore. Since the discovery of oil in Nigeria in the 1956, the country has been suffering the negative environmental consequences of oil development. Sabotage is another major cause of oil spillage in the country.

The transport and fate of spilled oil in water bodies are governed by physical, chemical, and biological processes that depend on the oil properties, hydrodynamics, meteorological and environmental conditions. These processes include advection, turbulent diffusion, surface spreading, evaporation, dissolution, emulsification, hydrolysis, photo-oxidation, biodegradation and particulation. Oil spill models have the capability of predicting the three-dimensional evolution of oil, including entrainment, subsurface transport, sedimentation, and refloating of spilled oil.

A new oil spill trajectory model has been developed. The results from an hypothetical simulation from a point around OPL 250 located about 150km off the Nigerian coastline shows that the simulated oil spill for wet season reached the shore (around Penington River) after 104hours (about 4.5 days). The oil spill will continue to move along the shoreline towards Escravos (i.e. in the direction of the longshore current). When the tide is high, the oil spill will move into the coastal lands and negatively impact the ecosystem.

By the end of the 104 hours a total of 94,525.660barrels of oil would have evaporated. This amount represents 16.88% of the 560,000 barrels of oil spilt. In addition the Slick area at the end of the 104hours would be 1782.058km².

Also during the dry season, the results from the model indicate that the oil spill reached the shore (at the entrance of Benin River) after 162hours (6.5days). The oil spill would then move towards Forcados (i.e. in the direction of the longshore current) around where its flow

would be affected by the longshore current coming from Penington end. The oil spill would be stationary at this point, and move into the coastlands during high waters.

By the end of the 162 hours a total of 147241.894barrels of oil would have evaporated. This amount represents 26.293% of the 560,000 barrels of oil spilt. In addition the slick area at the end of the 162hours would be 1628.440km².

Oil spill simulation model is used in oil response and contingency planning and as a tool in oil fate and impact assessment (Rossouw, 1998). In the event of an oil spill taking place, predictions of the slick can be supplied, provided that the necessary meteorological information is available (Rossouw, 1998).

To reduce the rate of oil incidents along the Nigerian Coast particularly as a result of vandalism, the Federal Government through an act of the National Assembly created the Niger Delta Development Commission (NDDC). Part of the responsibilities of the commission is to develop a master plan for the development of the Niger Delta, provide infrastructure and create an enabling environment for industrialisation and employment. There are also several other laws dealing with issues related to oil pollution in the environment. Also, standards for the development of the environmental sensitivity index maps for the coast of Nigeria have been developed by the Environmental Systems Research Institute (ESRI). These standards are to be used by all the oil companies to prepare ESI maps for their areas of operations in Nigeria.

4.2 Recommendations

The Nigeria Sat-1, would help in monitoring oil spill by providing the spill position which would serve as input data into the oil spill model. It would also give the extent of coastal water and coastal areas polluted. These information are vital for quick clean up of oil impacted areas.

In order to reduce the response time and qualify the decision-making process, application of Geographic Information Systems (GIS) as an operational tool has been suggested. Information on the exact position and size of the oil spill can be plotted on maps in GIS and a priority of the combat efforts and means according to the identified coastal sensitive areas can be carried out.

The creation of regional spill response centres along coastlines would help in managing oil spill problems. The centres will use oil spill models for combating oil spill problems. Using data collected with an airborne system to input one or several new starting point(s) into the model, will improve the accuracy of the further predictions

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BIOGRAPHICAL NOTES

Prof. Fatai O. A. Egberongbe

Prof F.O.A. Egberongbe is a Professor of Oceanography in Department of Surveying and Geoinformatics, University of Lagos, Nigeria. He is a Fellow of the Nigeria Institution of Surveyors and also a member of the Nigerian Hydrographic Society. He has several papers in internal journals and Conferences.

Dr. Peter Chigozie Nwilo

Dr. Nwilo has a Ph.D. in Environmental Resources from the University of Salford, United Kingdom. He also has a Bachelor of Science and a Master of Science degrees in Surveying from the University of Lagos. His Ph.D. Thesis is on sea Level Variations and the Impacts along the Coastal Areas of Nigeria.

He is a registered surveyor, a member of the Nigeria Institution of Surveyors, an Editorial Board Member of the *Journal of Environment Education and Information*, University of Salford, U.K., an Honorary Advisory Board Member of the *Encyclopedia of Life Support System* and an Editorial Board Member of the *African Geodetic Journal*. Dr. Nwilo had a fellowship Award of the European Community for his Ph.D.; and was a Federal Government of Nigeria scholar for his M.Sc. and B.Sc. degrees.

Dr. Nwilo has over 50 publications in journals and conferences in the areas of surveying, coastal management, oil spill, sea level variations, subsidence and environmental management.

Mr. Olusegun Temitope Badejo

Mr. O.T. Badejo graduated from the University of Lagos with a Bachelor of Science (B.Sc.) degree in Surveying in 1992. He also obtained a Master of Science (M.Sc.) degree in Surveying, in University of Lagos in 1996. His B.Sc. Project was on Sea Level Variation in a Coastal Seaport, while his M.Sc. research work was on Tidal Prediction Using Least Squares Approach. He is currently a Ph.D. candidate and also a Lecturer in Department of Surveying and Geoinformatics, University of Lagos. He is working on oil spill pollution transport and coastal processes. Mr. O.T. Badejo has over 10 publications.

CONTACTS

Fatai O. A. Egberongbe, Peter C. Nwilo and Olusegun T. Badejo
Department of Surveying and Geoinformatics
University of Lagos
Lagos
NIGERIA
Tel. + 234 8033375548, + 234 8035725644, + 234 8038636448
Email: pcnwilo@yahoo.com, shegunbadejo@yahoo.com