Oil Spill Model for Oil Pollution Control

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Key words: Oil Spill, Model

SUMMARY

Few studies have been carried out on oil spill trajectory and fate modeling. Limited modeling and observation suggest that oil spill move as the bulk water moves and that the water moves in concert with mass circulation including the influence of currents and tides. Additional influences in the movement of oil spill include vertical mixing and sedimentation.

A new oil spill trajectory model has been developed in this work. The relationship and the effect of waves induced current in the transport of oil spill on water was considered in the development of the model. Appropriate wave driven current equation was coupled with that of wind drift current, ocean current, tidal current and longshore current equations to generate a new model for advecting oil spill on coastal waters. Relevant equations for calculating the rate of spreading and evaporation of oil were also included in the oil spill model to enable the determination of the fate of oil spill.

A hypothetical spill site around OPL 250 located about 150km off the Nigerian coastline and another site located around Idoho, about 25km from Nigerian coastline were used as study areas for this work. Oil spill simulations with the new model were made for wet and dry seasons for these study areas.

Results from the new model indicate that for both wet and dry seasons, the ocean current is the major factor for moving the oil spill from the Atlantic Ocean to fairly deep waters. While the Longshore current and tides are the dominant forces that move the oil spill in shallow waters. Wind drift current and wave drift currents are secondary factors for moving the oil spill during wet and dry seasons.

Statistical analysis using Hotelling's T^2 indicates that the effect of adding waves parameters does not significantly affect the oil spill result. However, the accuracy of the oil spill model is improved by adding the wave parameters. Results from this work show that the incorporation of wave parameters into the oil spill model causes the oil spill to get to the shore a few hours earlier than when the wave parameters were neglected in the model.

There is a need for a better understanding of the coastal ecology so as to evaluate the significance of the impacts generated by oil spill incidents. The Federal Government in conjunction with oil parastatals and other non-governmental agencies should create more meteorological stations near the shoreline or on the coastal waters. The meteorological stations should provide real time or predicted meteorological data of the surrounding environment. This data would serve among other things as input data into oil spill models.

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1. INTRODUCTION

Oil releases have increasingly become a concern in recent years. Integrated oil/chemical fate and impact model systems may be used to quantify environmental impacts and damages resulting from real events, hypothetical spills (ecological risk assessment), and various response strategies (contingency planning), such that objective decision-making may occur (French McCay, 2006).

Studies on oil spill have shown that physical, chemical, and biological processes that depend on oil properties, hydrodynamics, and meteorological and environmental conditions govern the transport and fate of spilled oil in water bodies. These processes include advection, turbulent diffusion, surface spreading, evaporation, dissolution, emulsification, hydrolysis, photo-oxidation, biodegradation and particulation.

Few studies have been conducted on the subsurface advection of oil (Spaulding, 1995). Limited modeling and observation suggest that the dissolved and particulate oil move as the bulk water moves and that the water moves in concert with mass circulation including the influence of currents and tides (Spaulding, 1995). Additional influences in the subsurface movement include vertical mixing by Langmuir circulation (McWilliams and Sullivan, 2000).

The model due to Fay (1969, 1971) for oil spill spreading model is generally used by oil spill analysts to model oil spill dispersion. Dispersion is also modeled using a Fickian law that assumes a neutrally buoyant, noncohesive substance. Some composite oil slick models simply ignore horizontal dispersion and focus on the "center of mass" of the slicks. The National Oceanic and Atmospheric Administration's GNOME model uses a Fickian law. Others have developed heuristic methods with coefficients tuned to observed slick data. Examples include Morales et al. (1997) who have developed a random-walk method and Howlett et al. (1993) who break the spill into parcels called "spillets" and disperse them numerically.

Vertical dispersion and entrainment are the movements of oil droplets of sizes less than about 100 μm into the water column. MacKay developed an early model of entrainment based on the square of wind speed, the viscosity of oil, slick thickness, and surface tension (Reed 1992; ASCE, 1996). Tests of this model showed that it provided reasonable results at moderate wind speeds, but otherwise deviated from experimental values. Delvigne et al. (1987) and Delvigne (1993) developed a series of models based on a number of different flume tests, tank tests, and at-sea measurements.

Sinking is the mechanism by which oil masses that are denser than the receiving water are transported to the bottom. The oil itself may be denser than water, or it may have incorporated enough sediment to become denser than water. Sedimentation is the sorption of oil to

suspended sediments that eventually settle out of the water column and accumulate on the seafloor. There is a significant difference in the relative amount of oil incorporated by the two processes; sinking oil may contain a few percent sediment, whereas contaminated sediments accumulating on the seafloor will contain at most a few percent oil (McCourt and Shier, 2001).
Initial prediction of oil evaporation was carried out by using water evaporation equations such as the one developed by Sutton (1934). Later work of Mackay and colleagues (Mackay and Matsugu, 1973; Stiver and Mackay, 1984) was applied to describe the evaporation of crude oil through the use of mass-transfer coefficients as a function of wind speed and spill area. Stiver and Mackay (1984) further developed relationships between evaporative molar flux, mass transfer coefficient at prevailing wind speed, area of spill, vapor pressure of the bulk liquid, gas constant, and temperature.

Advection and spreading have been identified as the major factors responsible for moving oil spill on water by these models (Egberongbe *et al*, 2006). In many oil spills, evaporation is the most important process in terms of mass balance. Within a few days following a spill, light crude oils can lose up to 75 percent of their initial volume and medium crudes up to 40 percent. In contrast, heavy or residual oils will lose not more than 10 percent of their volume in the first few days following a spill. Most oil spill behavior models include evaporation as a process and as a factor in the output of the model (National Academy of Sciences, 2003).

Oil dissolution, emulsification, biodegradation, photosynthesis and sedimentation are minor factors affecting oil spill and are negligible because they are slow and gradual processes. They are however important in knowing the fate of oil spill over a long period of time.

Wind drift current, ocean current and tides are used by oil models for advecting oil spill on water. A fixed percentage (3-4%) of the speed of wind is assumed for the wind drift current. The bearing of the wind plus a deflection angle is taken as the bearing of the wind drift current. One hundred to one hundred and ten percent of the speed of real time ocean current or assumed ocean current from historic ocean current data are used in the models. The bearing of the ocean current is also obtained in real time or from historic data. Some of the oil models obtained their tidal information from existing tidal or hydrodynamic models, while others neglect the effect of tides in their models. Wind drift speed and bearing, ocean current speed and bearing, and tidal speed and bearing are vector summed in oil spill models to get the speed and bearing of oil spill on water.

2. DEVELOPMENT OF A NEW MODEL FOR OIL POLLUTION CONTROL

Despite the fact that many oil spill models have been developed, most of the existing models have not been able to accurately track the movement of oil spill on coastal waters. The reasons for this are that many assumptions have been made in the development of these models. While some of the models assume a certain percentage of wind velocity as the oil drift factor, some ignore other factors that move oil spill on water. Furthermore ignorance of the physical and meteorological characteristics of the surrounding water bodies has led to the failure of the deployment of these models.

In this work a new model has been developed. In the development of this model, emphasis is laid on identification of all major factors that govern the movement of oil on water. We have also used theoretical mathematical equations that govern these major factors to develop the new oil spill model. The following is the thereotical framework that was used to develop the model:

1. Two Dimensional Hyperbolic Wind Drift Equation Based on Newton's Law.
2. Airy's Eulerian Wave Theory with Taylor's Series Expansion.
3. Tidal Current Analysis by Dean and Dalrymple.
4. Fay's Spreading Laws.
5. MacKay's Evaporative Formula.

2.1 Two Dimensional Hyperbolic Wind Drift Equation

This work adopts the two dimensional hyperbolic wind drift equations given by Officer (1976) and Kelley (2003). These equations are based on Newton's second law of motion. As the wind blows over the surface, water is dragged along forming the wind drift current. The bearing of the wind drift current depends on the depth beneath the water surface and latitude. Officer (1976) expressed the final equation of the wind drift current in terms of hyperbolic functions as:

$$S_X = A\,Cosh\,\alpha\,(d-z)\,Sin\,\alpha\,(d-z) + B\,Sinh\,\alpha\,(d-z)\,Cos\,\alpha\,(d-z) \qquad 2.1a$$

$$S_Y = A\,Sinh\,\alpha\,(d-z)\,Cos\,\alpha\,(d-z) - B\,Cosh\,\alpha\,(d-z)\,Sin\,\alpha\,(d-z) \qquad 2.1b$$

$$S_{WDC} = \sqrt{(S_X^2 + S_Y^2)} \qquad 2.2$$

where

S_X is the speed of wind drift current along X direction (m/s)

S_Y is the speed of wind drift current along Y direction (m/s)

S_{WDC} is the radial speed of wind drift current (m/s)

$$A = \left(\frac{T}{\alpha\rho N_z}\right)\frac{(Cosh\,\alpha d\;Cos\;\alpha d + Sinh\;\alpha d\;Sin\;\alpha d)}{(Cosh\;2\alpha d + Cos\,2\alpha d)} \qquad 2.3$$

$$B = \left(\frac{T}{\alpha\rho N_z}\right)\frac{(Cosh\,\alpha d\;Cos\;\alpha d - Sinh\;\alpha d\;Sin\;\alpha d)}{(Cosh\;2\alpha d + Cos\,2\alpha d)} \qquad 2.4$$

$$\alpha = \sqrt{(\omega_0\,Sin\,\varphi\,/\,N_z)} \qquad 2.5$$

$$T = -\rho\,N_z\,\frac{\partial v_X}{\partial z}\quad (\mathrm{N/m^2}) \qquad 2.6$$

z is the depth of liquid measured positively downwards (z = 0 on water surface).
d is the bottom depth (m).
ρ is the density of sea water (kg/m^3)
$\frac{\partial v_X}{\partial z}$ is the rate of change of the speed of the wind drift in the X direction with respect to depth

v = Coefficient of kinematic viscosity of fluid (m^2/s)
ω_0 = Angular velocity of earth's rotation = $\frac{2\pi}{T^1}$ (rad/s)
T^1 = Period of the earth's rotation $\left(\frac{2\pi}{24*60*60}\right)$ = 0.0000729 rad/s.

Due to the difficulty in determinining $\frac{\partial v_X}{\partial z}$ in equation 2.6, Kelley (2003) gave the following formular for the tangential wind stress (T):

$$T = \rho_a C_d U^2 \quad \text{(N/m}^2\text{)} \qquad 2.7$$

where

ρ_a = Air Density (kg/m^3)

C_d = Drag Coefficient (0.001 for calm sea, 0.002 for rough sea)

U= Wind Speed (m/s)

Buranapratheprat and Tanjaaitrong (2000) stated that the deflection angle of the wind drift current depends on latitude. For latitudes between 10^0 N and 10^0 S, the deflection angle (δ) reduces linearly with latitude φ and can be approximated as:

$$\delta = 33^O(\varphi/10) \qquad 2.8$$

The wind drift bearing is therefore the sum of the wind bearing and the deflection angle expressed as:

$$\alpha_{WDC} = \text{Wind bearing} + 33^O(\varphi/10) \qquad 2.9$$

where

α_{WDC} = Wind Drift bearing (^{o})

2.2 Airy's Eulerian Wave Theory with Taylor's Series Expansion

The Eulerian wave drift current in this work is based on Airy's wave theory with a Taylor's series expansion given by Sobey and Barker (1997). The wave drift current equations depend on wave speed, wave frequency, wave period and wave number. The wave number is determined by dispersion relation given by Lamb (1932) and solved using Newton Raphson's iteration method. The wave averaged Eulerian surface drift is:

$$S_{SWD} = 0.5(ka)^2 C \qquad 2.10$$

where

S_{SWD} = Speed of surface wave drift (m/s)
k = Wave number (cm^{-1})
a = Wave amplitude (m)
C = Wave speed (m/s)
Wave Speed (C) = Wave frequency/Wave number
Wave frequency (ω) = $\frac{2\pi}{T_w}$
T_w = Wave period (s)

Wave number (k) can be determined by the following dispersion relation given by Lamb (1932):

$$\omega^2 = gk \tanh(kd) \qquad 2.11$$

where
ω = Wave frequency (Hz)
g = Force of gravity (m/s^2)
k = Wave number (cm^{-1})
d = Water depth (m)

The dispersion equation in equation 2.11 above can only be solved iteratively. Newton Raphson's iteration method given in equation 2.12a was used to solve the dispersion equation:

$$k_{n+1} = k_n - F(k)/F^{'}(k) \qquad 2.12a$$

where

$$F'(k) = d/dk(F(k))$$

$$k_{n+1} = k_n - ((\omega^2 - gk \tanh(kd)/(-gkd\,\mathrm{sech}^2(kd) - g\tanh(kd))) \qquad 2.12b$$

$$\tanh(kd) = (e^{kd} - e^{-kd})/(e^{kd} + e^{-kd}) \qquad 2.13$$

Initial approximation for k given below can be determined from shallow water approximation where $\tanh(kd) = kd$. Substituting (kd) for tanh(kd) gives:

$$\omega^2 = gk^2 d$$

$$k = \sqrt{(\omega^2 / gd)} \qquad 2.14$$

Initial approximation for k can also be determined from deep water approximation where tanh (kd) = 1

$$k = \frac{\omega^2}{g} \qquad 2.15$$

ω = Wave frequency (Hz)

α_{SWD} = direction of the Eulerian surface wave drift (the same as that of the wind).

2.3 Tidal Current Analysis

The tidal equation for determining horizontal speed of tide in this work is based on tidal current analysis by Dean and Dalrymple (1984). The tidal current analysis is a function of the amplitude of the tide, the wave frequency, wave number, water depth, distance and time. The tidal currents experienced along the Nigerian Coast are semi-diurnal tides with a period of approximately 25hours (Nwilo, 1995). Tides are significant in moving oil along the creeks. During the floods the oil spill moves upstream, and at times of ebbs, the water and oil spill recede.

The horizontal speed of a particle of tide along the wave direction from origin is given by Dean and Dalrymple (1984) as:

$$S_{TIDE} = a\omega \frac{Cosh(k(h+z))}{Sinh(kh)} Cos(kx - \omega t) \qquad 2.16$$

For shallow waters and at water surface, the horizontal speed of a particle of tide becomes

$$S_{TIDE} = a\omega Cos(kx - \omega t) \qquad 2.17$$

$$\omega = \text{Wave frequency } \left(\frac{2\pi}{T}\right) \qquad 2.18$$

T is wave period
h is water depth (m)
a is Amplitude of tide (Half tidal range (m))
t is time (0-25 hour)
k is wave number (given in section 2.2)
x is distance (m)

The assumption made here is that the heights of the two high waters and the two low waters in a day are the same and that they have a regular period of 12.5hours. The average of the two high waters and the two low waters predicted by Nigerian Navy tide tables is used to compute the amplitude of the tide for a given area. This amplitude together with the phase angle of the tide will be used to predict the speed of the tidal current. The times of high and low waters in a day will be related to the times of crests and troughs of our tidal curve. Figure 2.1 shows a tidal current curve with amplitude 0.44m and phase difference of 104^0. The high waters will occur at 3.125hr and 15.625hr while the low waters will occur at 9.375hr and 21.875hr. The periods of high waters and low waters are always the same on the assumed tidal current curve for any combination of amplitude and phase difference for a tide with a period of 12.5hrs. The time of the tide on our assumed tidal current curve is related to the actual time of tide by the relationship equation below:

$$t = 3.125 + (t_{actual} - THW) \qquad 2.19$$

where
t = Time of tide on our assumed tidal curve
t_{actual} = Actual time of the day (0-24hr)
THW = Time of high water.
Thus for any given time t_{actual}, the corresponding time t on our assumed tidal curve can be calculated by equation 2.19 while the speed of the tide would be calculated by equation 2.17.

The bearing of tide (α_{TIDE}) for a progressive tide is the wind or wave bearing during floods and opposite the wind or wave bearing during ebbs (Canadian hydrographic service, 2005).

$$\alpha_{TIDE} = \text{Wind Bearing } \pm 180^{O} \qquad 2.20$$

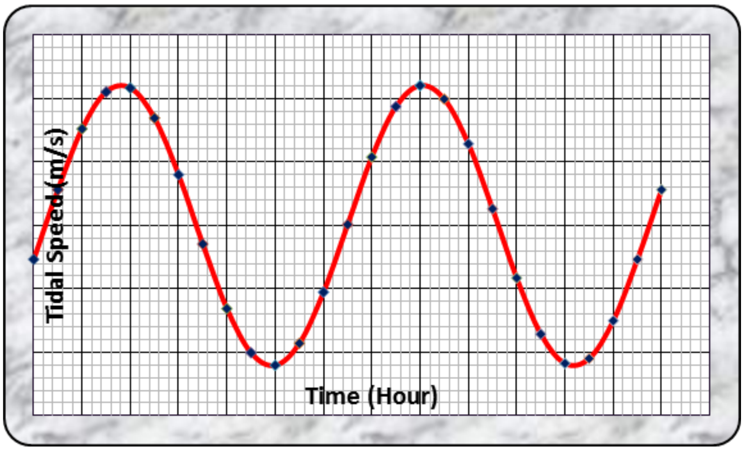

Figure 2.1: Tidal Current Curve

2.4 Fay's Spreading Laws

Fay's spreading theory of 1971 was used in this work. 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 balance between surface tension and viscous forces governs the last phase. To apply this theory, the geometry for the oil slick is simplified into either one-dimensional or radial form. The criterion 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 (Reddy and Brunet, 1997). Table 2.1 shows Fay's spreading laws.

Table 2.1: Spreading Law for Oil Slicks

Spreading Phase	One Dimensional Spreading Width (m)	Axi Symmetrical Spreading Radius R (m)
Gravity-Inertia	$1.39(\Delta gAt^2)^{1/3}$	$1.14(\Delta gVt^2)^{1/4}$
Gravity-Viscous	$1.39(\Delta gA^2t^{3/2v-1/2})^{1/4}$	$0.98(\Delta gV^2t^{3/2v-1/2})^{1/6}$
Surface Tension Viscous	$1.43(\sigma^2t^3\rho_w{}^{-2v-1})^{1/4}$	$1.60(\sigma^2t^3\rho_w{}^{-2v-1})^{1/4}$

where

$\Delta = 1 - \left(\frac{\sigma}{\rho_w}\right)$

V = Volume of oil slick (m^3)
v = kinematic viscosity (m^2/s)
t = time (s)
g = force of gravity (m/s^2)
ρ_w = Density of water (g/cm^3)
A = Spill area (m^2)
σ = Density of oil (g/cm^3)

Once oil is released on water, the process of spreading takes place immediately. Fay final slick area of oil is given by (Kung et al, 1997) as:

$$A_f = 10^5 V^{3/4} \tag{2.21}$$

V = Total volume of the oil slick (m^3) 2.22

In this work, oil spill is assumed to spread radialy under steady gravity and viscous forces, thus Fay's radial spreading formula for gravity and inertial forces is used.

The formular for the radial spreading for gravity inertial (1-4 hours) after oil spillage is given by:

$$R = 1.14(\Delta g V t^2)^{1/4} \tag{2.23}$$

The formular for the radial spreading for gravity viscous (4hrs-10 days) after oil pillage is given by:

$$R = 0.98((\Delta g V^2 t^{1.5}) / v^{0.5})^{1/6} \tag{2.24}$$

where

$$\Delta = 1 - \left(\frac{\sigma}{\rho_w}\right) \tag{2.25}$$

V = Volume of oil slick (m^3)
v = Kinematic viscosity (m^2/s)
t = Time (s)
g = Force of gravity(m/s^2)
R = Radial distance (m)

2.5 MacKay's Evaporative Formula

The formula developed by (Mackay *et al*, 1980) was used in this work to calculate the evaporation rate of oil. The amount of oil evaporated at a time t after the oil spillage is given by:

$$F = (1/C)(\ln P_0 + \ln(CK_e t + 1/P_0)) \tag{2.26}$$

Where

$C = 1158.9 API^{-1.1435}$ 2.27

$API = \left(\frac{141.5}{\sigma}\right)^{-131.5}$ 2.28

σ = density of oil

$\ln P_0 = 10.6\ (1 - \frac{T_0}{T_e})$ 2.29

$P_0 = EXP(\ln P_0)$ (i.e. Antilog of $\ln P_0$)

T_0 is the initial boiling point in degrees Kelvin.

T_e is the ambient air temperature

$T_0 = 542.6 - 30.275 API + 1.565 API^2 - 0.03439 API^3 + 0.0002604 API^4$ 2.30

$K_e t$ is the " evaporative exposure" term, which varies with time and environmental conditions.

$K_e = \frac{K_m A V_m}{RTV}$ 2.31

$K_m = 0.0025 W^{0.78}$ 2.32

W = Wind forcing (m/s)

$A = (10^5) * V^{0.75}$ 2.33

A is spill area (m^2)

V is the spill volume in cubic meters.

V_m is molar volume in cubic meters per mole (for fuel oils V_m is approximately 200*10^{-6} m^3/mole)

R is the gas constant (i.e. $82.06 * 10^{-6}$ atm $m^3 mol^{-1} K^{-1}$).

2.6 Equations for Ocean 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. During the Dry season, the Benguela current moves the oil spill. The speed of the ocean current is given by:

S_{OC} = 100 percent of Speed of Ocean current.

The direction of the ocean current is simply the direction of the ocean current at the time of observation and is represented as α_{OC} .

α_{OC} = Bearing of Ocean Current

2.7 Model for Longshore Current

Although waves tend to become parallel with the coast as a result of refraction, they usually break at a slight angle to the shore, with the result that a littoral or longshore current is induced and is effective in moving a mass of water slowly along the coast. Longshore drift is the prevalent sediment transport mechanism along the Nigerian coastline and is basically within the first 5km kilometres offshore. The whole magnitude of the speed of the longshore current is responsible for moving oil spill along the coastline. The oil spill will also move in the direction or bearing of the longshore current. The speed and direction of the Longshore current is represented as S_{LC} and α_{LC} respectively in this work.

S_{LC} = Speed of Longshore Current
α_{LC} = Bearing of Longshore Current

2.8 Final Equations of the Oil Spill Model

An integrated dynamic oil spill trajectory model for advecting oil spill on open- water was evolved after finding the resultant of the equations for the wind drift current speed and bearing, the Eulerian surface wave drift speed and bearing, tidal speed and bearing, ocean current speed and bearing and longshore current speed and bearing (Egberongbe *et al*, 2006). The resultant of the equations (speed of oil spill) is given by:

$$S_{NM} = ((S_{WDC} Sin\alpha_{WDC} + S_{SWD} Sin\alpha_{SWD} + S_{TIDE} Sin\alpha_{TIDE} + S_{OC} Sin\alpha_{OC} + S_{LC} Sin\alpha_{LC})^2 + (S_{WDC} Cos\alpha_{WDC} + S_{SWD} Cos\alpha_{SWD} + S_{TIDE} Cos\alpha_{TIDE} + S_{OC} Cos\alpha_{OC} + S_{LC} Cos\alpha_{LC})^2)^{1/2} \qquad 2.34$$

The angle between the resultant and the x-axis is given by:

$$\alpha_{NM} = Tan^{-1} \frac{(S_{WDC}\ Sin\ \alpha_{WDC} + S_{SWD}\ Sin\ \alpha_{SWD} + S_{TIDE}\ Sin\ \alpha_{TIDE} + S_{OC}\ Sin\ \alpha_{OC} + S_{LC}\ Sin\ \alpha_{LC})}{(S_{WDC}\ Cos\ \alpha_{WDC} + S_{SWD}\ Cos\ \alpha_{SWD} + S_{TIDE}\ Cos\ \alpha_{TIDE} + S_{OC}\ Cos\ \alpha_{OC} + S_{LC}\ Cos\ \alpha_{LC})} \qquad 2.35$$

where

S_{NM}	=	Speed of oil spill on open water
α_{NM}	=	Bearing of oilspill on open water
S_{WDC}	=	Speed of wind drift current.
α_{WDC}	=	Bearing of wind drift current.
S_{SWD}	=	Speed of Eulerian surface wave drift current.
α_{SWD}	=	Bearing of Eulerian surface wave drift current.
S_{TIDE}	=	Speed of tide.
α_{TIDE}	=	Bearing of tide.
S_{OC}	=	Speed of ocean current.
α_{OC}	=	Bearing of ocean current.

S_{LC} = Speed of longshore current
α_{LC} = Bearing of longshore current

The equations for S_{WDC}, α_{WDC}, S_{SWD}, α_{SWD}, S_{TIDE}, α_{TIDE}, are given in equations 2.2, 2.9, 2.10, 2.15, 2.17 and 2.20 respectively, while S_{OC}, α_{OC}, S_{LC} and α_{LC} are explained in sections 2.6 and 2.7.

The model equations for spreading are given by equations 2.21, 2.23 and 2.24. Equation 2.26 is the model equation for evaporation.

2.9 Study Areas and Model Implementation

Two study areas were used in this work. A hypothetical spill site around OPL 250 located about 150km off the Nigerian coastline was chosen as study area I (Nwilo and Badejo, 2006). The actual spill position is longitude 4^{o} 30' 46.20" E and latitude 4^{o} 25' 39.80" N. Simulations were made for wet and dry seasons for study area I. Study area II is located around Idoho, about 25km from Akwa Ibom State coastline. The oil spill point is Longitude 8^{o} 00', Latitude 4^{o} 20'N. Simulations were also made for wet and dry seasons for study area II.

The OILMAP model was also used to make simulations for the same study area above for wet and dry seasons.

3. RESULTS AND ANALYSIS OF RESULTS

The sections in this chapter contain the results of oil spill simulation with the model developed in this work and the results of other models. Hypotheses testing and analysis of the results were also carried out in this chapter.

3.1 Results

The following sub sections contain the oil spill trajectory model's results for oil spill simulation in study area I and study area II for both wet and dry seasons

3.1.1 Results of Oil Spill Simulation with the New Model for Study Area I (Wet Season)

The summary of the results in wet season is given in Table 3.1. The simulated oil spill points for all the phases for the wet season were plotted in ArcGIS software, which is linked with the model in ArcGIS Visual Basic environment. The Oil Spill Trajectory for the wet season in Study Area I is shown in Figure 3.1. The result for wet season for the study area indicate that the simulated oil spill will reach the shore line between Kulama River and Penington River after 122hours (5days), and then move towards Ramos river along the direction of the longshore current. The oil spill will move inlands during high tides and back to its position along the shoreline when the tides are low. The oil spill will reach Ramos River in 150 hours.

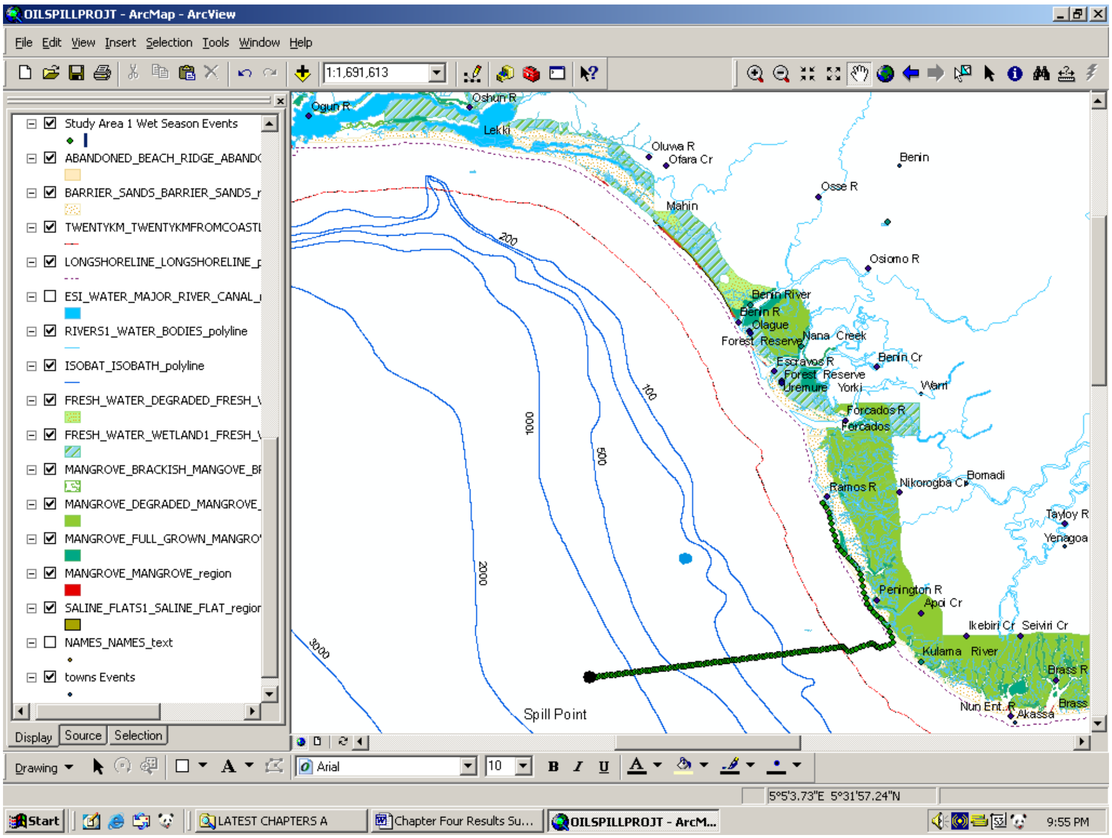

Table 3.1: Summary of Results of New Oil Spill Model for Study Area I During the Wet Season

	Very Deep Waters (500m)	Deep Waters (50m)	Fairly Deep Waters (15m)	Shallow Waters (5m)
Oil Spill Speed	0.294m/s	0.285-0.304 m/s	0.178-0.476m/s	0.584-0.713m/s
Oil Spill Bearing	83.09- 83.10 deg	81.59- 84.58deg	66.99 –135.12deg	311.69 – 349.67deg
Ocean Current Speed	0.233m/s	0.233m/s	0.233m/s	-
Ocean Current Bearing	90^o (East)	90^o (East)	90^o (East)	-
Wind Drift Speed	0.065m/s	0.065m/s	0.051m/s	0.018m/s
Wind Drift Bearing	59.61 deg	59.90deg	59.99deg	60.04deg
Wave Drift Speed	0.003m/s	0.004m/s	0.006m/s	0.011m/s
Wave Drift Bearing	45 deg	45deg	45deg	45deg
Tidal Speed	-	0 – 0.013 m/s	0-0.22m/s	0-0.22m/s
Tidal Bearing	-	45/225	45/225deg	45/225deg
Longshore Current Speed	-	-	-	0.61m/s

Longshore Current Bearing	-	-	-	330 deg

3.1.2 Results of Oil Spill Simulation with the New Model for Study Area I (Dry Season)

The summary of the results in dry season is given in Table 3.2. The simulated oil spill points for all the phases for the dry season in study area I were plotted in ArcGIS environment, which is linked with the oil spill trajectory model in Visual Basic environment and shown in Figure 3.2.

The result for the dry season for the study area indicates that the simulated oil spill will reach the shore in 213 hours and get to Benin River after 222 hours (nine days). The oil spill will pollute Benin River and it's adjoining areas. The oil spill will move inlands during high tides and back to its position along the shoreline when the tides are low.

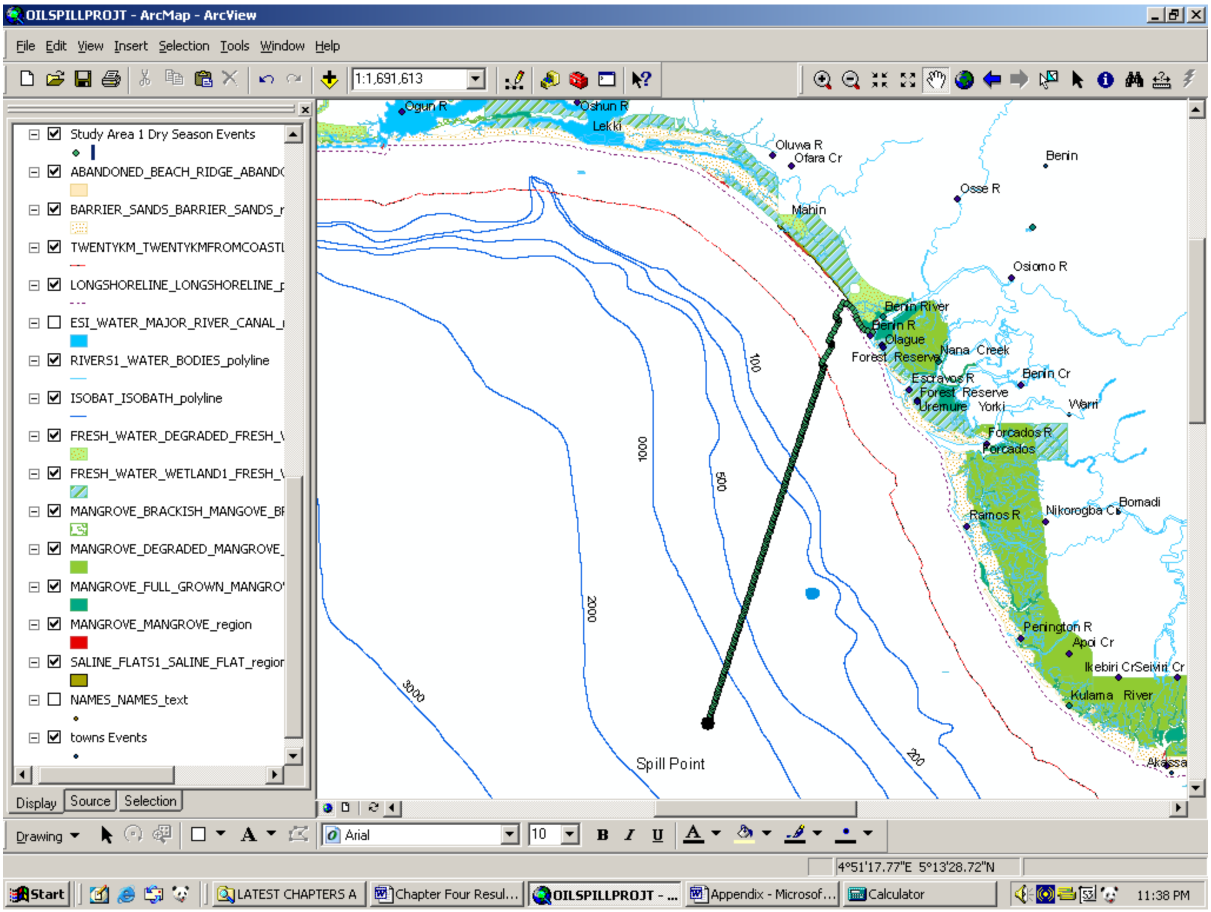

Table 3.2: Summary of Results of New Oil Spill Model for Study Area I During the Dry Season

	Very Deep Waters (500m)	Deep Waters (50m)	Fairly Deep Waters (15m)	Shallow Waters (5m)
Oil Spill Speed	0.221-0.222m/s	0.207-0.231 m/s	0.101 – 0.416m/s	0.398 – 0.460m/s
Oil Spill Bearing	17.80- 18.12 deg	16.99 – 20.00 deg	294.47 – 30.95deg	104.72 – 160.016deg

Ocean Current Speed	0.17m/s	0.17m/s	0.17m/s	-
Ocean Current Bearing	0° (North)	0° (North)	0° (North)	-
Wind Drift Speed	0.076-0.077m/s	0.075-0.076m/s	0.060m/s	0.022m/s
Wind Drift Bearing	59.61 deg	62.56deg	63.63deg	64.35deg
Wave Drift Speed	0.003m/s	0.004m/s	0.006m/s	0.011m/s
Wave Drift Bearing	45 deg	45deg	45deg	45deg
Tidal Speed	-	0 – 0.013 m/s	0-0.221m/s	0.028 - 0.217m/s
Tidal Bearing	-	45/225	45/225deg	45/225deg
Longshore Current Speed	-	-	-	0.390m/s
Longshore Current Bearing	-	-	-	135 deg

3.1.3 Results of Oil Spill Simulation with the New Model for Study Area II (Wet Season)

The results of the oil spill simulation with the new model for Study Area II is given in Table 3.3. The simulated oil spill points for all the three phases for the wet season in study area II were plotted in ArcGIS software which is linked with the model in ArcGIS Visual Basic environment. The Oil Spill Trajectory for the wet season is shown in Figure 3.3.

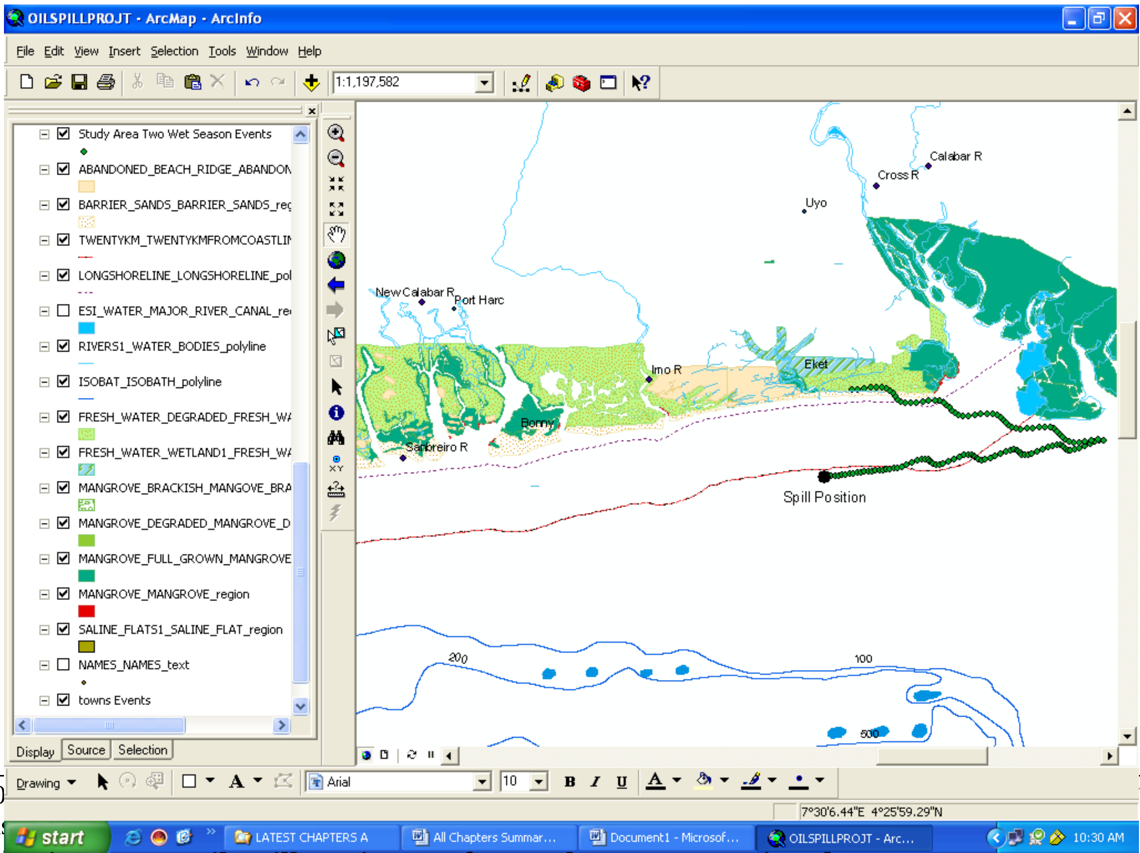

Figure 3.3: Oil Spill Trajectory for Study Area II During the Wet Season

The spill point for study area II is just about 20km from the shoreline, and at a depth of about 25m. During the wet season the simulated oil spill will get to the shoreline at Bakassi Peninsula in 88hours (3.5days) and move westwards along the Nigerian coastline in the direction of the longshore current The oil spill will pollute the Bakassi peninsula and the eastern coast of Nigeria as it moves in the direction of the longshore current. Tidal action will make the impact of the oil spill enormous as it moves in and out of the wetlands.

Table 3.3: Summary of Results of New Oil Spill Model for Study Area II During the Wet Season

	Deep Waters (25m)	**Fairly Deep Waters (15m)**	**Shallow Waters (5m)**
Oil Spill Speed	0.285 – 0.305 m/s	0.178 – 0.476m/s	0.307 – 0.512m/s
Oil Spill Bearing	81.41 – 84.38 deg	66.92 – 135.04 deg	261.82 – 320.93 deg
Ocean Current Speed	0.233m/s	0.233m/s	-
Ocean Current Bearing	90^o (East)	90^o (East)	-
Wind Drift Speed	0.065m/s	0.052m/s	0.018m/s
Wind Drift Bearing	59.30 deg	59.38 deg	59.61 deg
Wave Drift Speed	0.005m/s	0.006m/s	0.011m/s
Wave Drift Bearing	45 deg	45 deg	45 deg
Tidal Speed	0 – 0.013 m/s	0-0.221m/s	0 - 0.221 m/s
Tidal Bearing	45/225	45/225deg	45/225deg
Longshore Current Speed	-	-	0.380m/s
Longshore Current Bearing	-	-	280 deg

3.1.4 Results of Oil Spill Simulation with the New Model for Study Area II (Dry Season)

The summary of the results of the oil spill simulation with the new model for study area II during the dry season is given in Table 3.4. The simulated oil spill points for all the phases for the dry season in study area II were plotted in ArcGIS software which is linked with the model in ArcGIS Visual Basic environment. The Oil Spill Trajectory for the dry season is shown in Figure 3.4.

As stated in the previous section, the spill point for study area II is just about 20km from the shoreline, and at a depth of about 25m. During the dry season the simulated oil spill will get to the shoreline around Eket in 35hours (1.5days) and move westwards towards Bonny in the direction of the longshore current parallel to the coastline. The oil spill will move inlands during floods and recede during ebbs. The coastal wetlands and farmlands will be polluted as the oil spill move westwards.

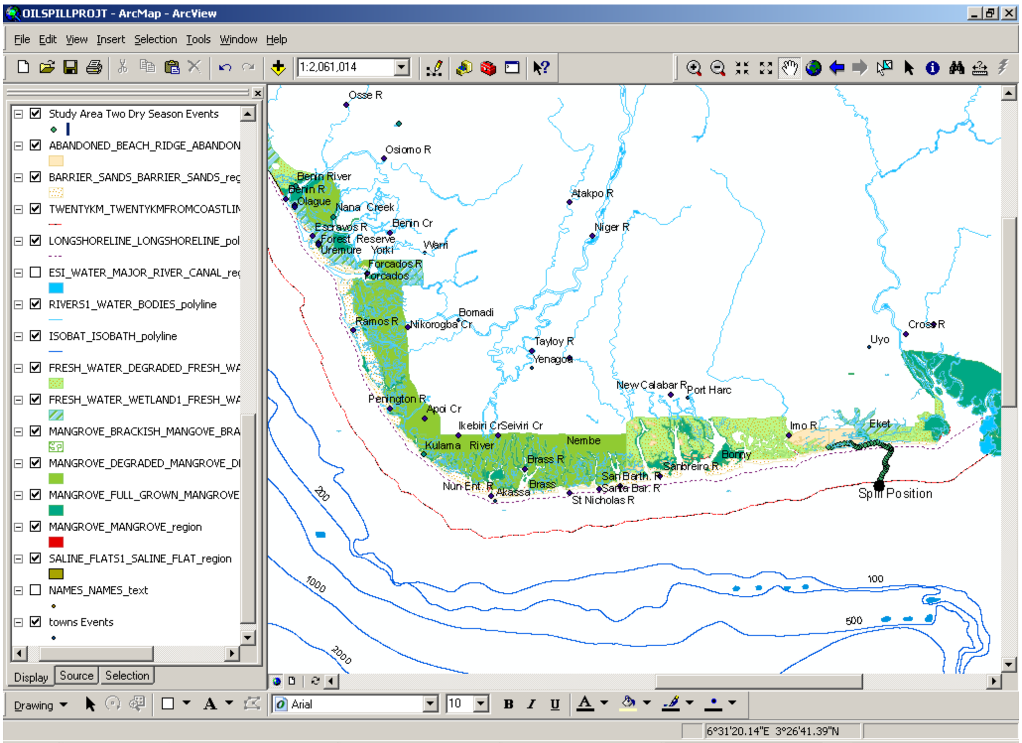

Figure 3.4: Oil Spill Trajectory for Study Area II During the Dry Season

Table 3.4: Summary of Results of New Oil Spill Model for Study Area II During the Dry Season

	Deep Waters (25m)	**Fairly Deep Waters (15m)**	**Shallow Waters (5m)**
Oil Spill Speed	0.213 – 0.219 m/s	0.105 – 0.420m/s	0.250 – 0.532 m/s
Oil Spill Bearing	16.71 – 17.52 deg	296.42 – 30.40 deg	252.84 – 308.29 deg
Ocean Current Speed	0.17m/s	0.17m/s	-
Ocean Current Bearing	0^o (North)	0^o (North)	-
Wind Drift Speed	0.078m/s	0.061 - 0.062m/s	0.022 m/s
Wind Drift Bearing	59.30 deg	59.37 deg	59.93 deg
Wave Drift Speed	0.005m/s	0.006m/s	0.011m/s
Wave Drift Bearing	45 deg	45 deg	45 deg
Tidal Speed	0 – 0.013 m/s	0-0.221m/s	0 - 0.221 m/s
Tidal Bearing	45/225	45/225deg	45/225deg
Longshore Current Speed	-	-	0.380m/s

Longshore Current Bearing	-	-	267 deg

3.2 Hotelling T^2 Statistical tests

Hotellings T^2 Statistical tests was carried out to check whether there is any significant difference in the means of the oil spill speed and oil spill bearing for the new model with wave parameters and for the new model without wave parameters for wet and dry seasons in Study Area I. A computer programme was written in Visual Basic 6.0 for the purpose of carrying out the test. Figure 3.5 shows the Graphical User Interface of the Hotellings Statistical test in Visual Basic 6.0 environmemt.

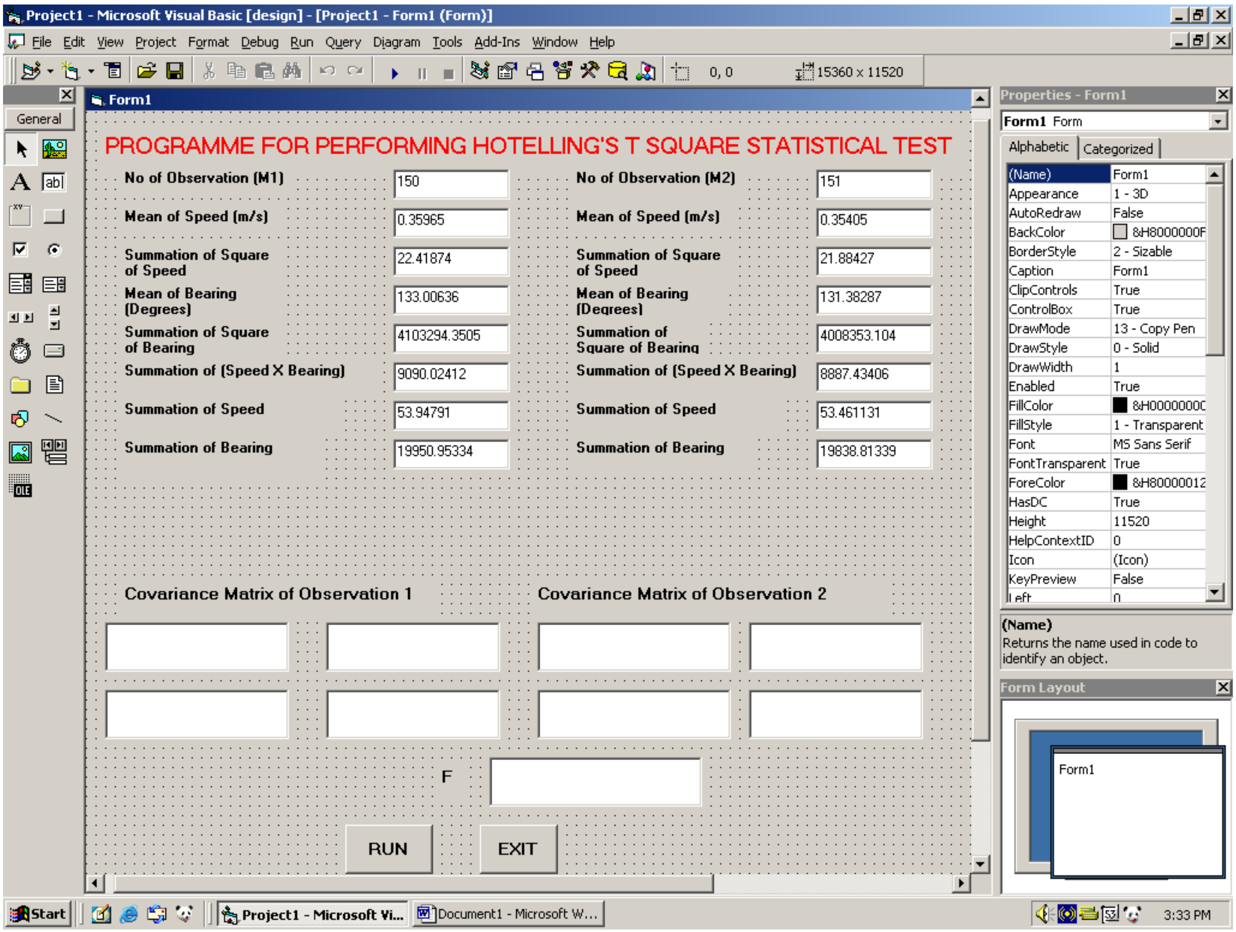

Figure 3.5: Visual Basic 6.0 Graphical User Interface for Performing Hotellings T^2 Statistical Test

Olaleye (1992) gave the following matrices and sets of equations for carrying out Hotelling's T^2 statistical test.

Row Cross Product

$$\begin{bmatrix} \sum_{i=1}^{m} Speed^2 & \sum_{i=1}^{m} (Speed\ .Bearing) \\ \sum_{i=1}^{m} (Speed\ .Bearing) & \sum_{i=1}^{m} Bearing^2 \end{bmatrix}$$

Mean Corrected Sum of Squares and Cross Products (SSCP) Matrix

$$\begin{bmatrix} \left(\sum_{i=1}^{m} Speed^2\right)' & \left(\sum_{i=1}^{m} [Speed\ .Bearing]\right)' \\ \left(\sum_{i=1}^{m} [Speed\ .Bearing]\right)' & \left(\sum_{i=1}^{m} Bearing^2\right)' \end{bmatrix}$$

where

$$(\textstyle\sum_{i=1}^{m} Speed^2)' = (\sum_{i=1}^{m} Speed^2) - \frac{(\sum_{i=1}^{m} Speed)^2}{m}$$

m is the number of observations

$$(\textstyle\sum_{i=1}^{m} Bearing^2)' = (\sum_{i=1}^{m} Bearing^2) - \frac{(\sum_{i=1}^{m} Bearing)^2}{m}$$

$$(\textstyle\sum_{i=1}^{m} [Speed\ .Bearing])' = (\sum_{i=1}^{m} [Speed\ .Bearing]) - \frac{(\sum_{i=1}^{m} Speed)(\sum_{i=1}^{m} Bearing)}{m}$$

Covariance Matrix

The Covariance Matrix (C) is given by:

$$C = \frac{S}{m}$$

Where S is Mean Corrected (SSCP) Matrix and m is no of observation.

Pooled Covariance Matrix

The Pooled sample covariance matrix of the new model with wave parameters and without wave parameters for any season is:

$$C_p = \frac{[(M_1 - 1)C_1 + (M_2 - 1)C_2]}{M_1 + M_2 - 2}$$

$$T^2 = \frac{M_1 M_2 (\bar{X}_1 - \bar{X}_2)^T C_p^{-1} (\bar{X}_1 - \bar{X}_2)}{M_1 + M_2}$$

$\bar{X}_1, \bar{X}_2$ are mean vectors

$\bar{X}_1$ is the mean of speed

$\bar{X}_{2,}$ is the mean of bearing

$$F = \frac{(M_1+M_2-P-1)T^2}{(M_1+M_2-2)P}$$

M_1 is the no of observations in model with wave parameters
M_2 is the no of observations in model without wave parameters
Reject Ho: If $F > F_{1-\alpha}$ $(P, M_1 + M_2 - P - 1)$
Let α: = 0.05

For both the wet and dry seasons, $F < F_{1-\alpha}$, we therefore accepted H_O that is there were no significant differences between the results of the new model with wave parameters and without wave parameters during the wet and dry seasons. Details of the statistical tests can be found in Badejo (2008). Statistical results from the Hotelling's T^2 tests show that there was no significant diffence in adding the wave parameters to the model. We however noted that when the wave parameters were added to the model, the oil spill got to shore about an hour earlier during the wet season in study area I and eight hours earlier during the dry season in study area I. In addition, the results from the model when the wave parameters were added to it indicated that the wetlands would be subjected to more degradation. Figures 3.6 and 3.7 show the results of the model when the wave parameters were added and and removed from the model for both wet and dry seasons in study area I.

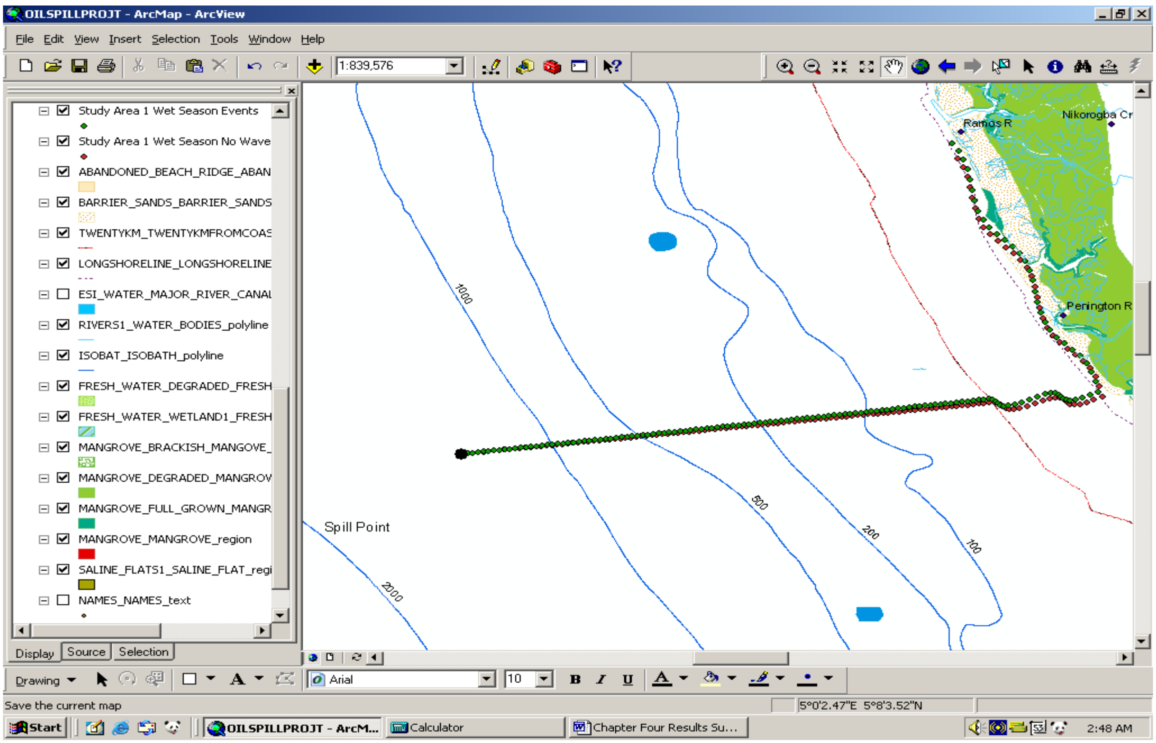

Figure 3.6: Oil Spill Trajectories for the Wet Season in Study Area I With Wave Parameters and Without Wave Parameters

Oil spill simulations were also made with the hydrodynamic models developed by Hang et al. (1989) and Kung et al. (1997**).** Statistical tests using Hotelling's T^2 indicated that there was no significant difference in the results from our model and that of Hang et al. (1989) while there was a significant difference in our results and that of Kung et al. (1997). Details of the statistical tests can be found in Badejo (2008). The results from the new model also indicated that oil spill would impact the same part of our coastal areas as signified by OILMAP trajectory model during the dry season. The results from OILMAP for both wet and dry seasons are given in figures 3.8 and 3.9.

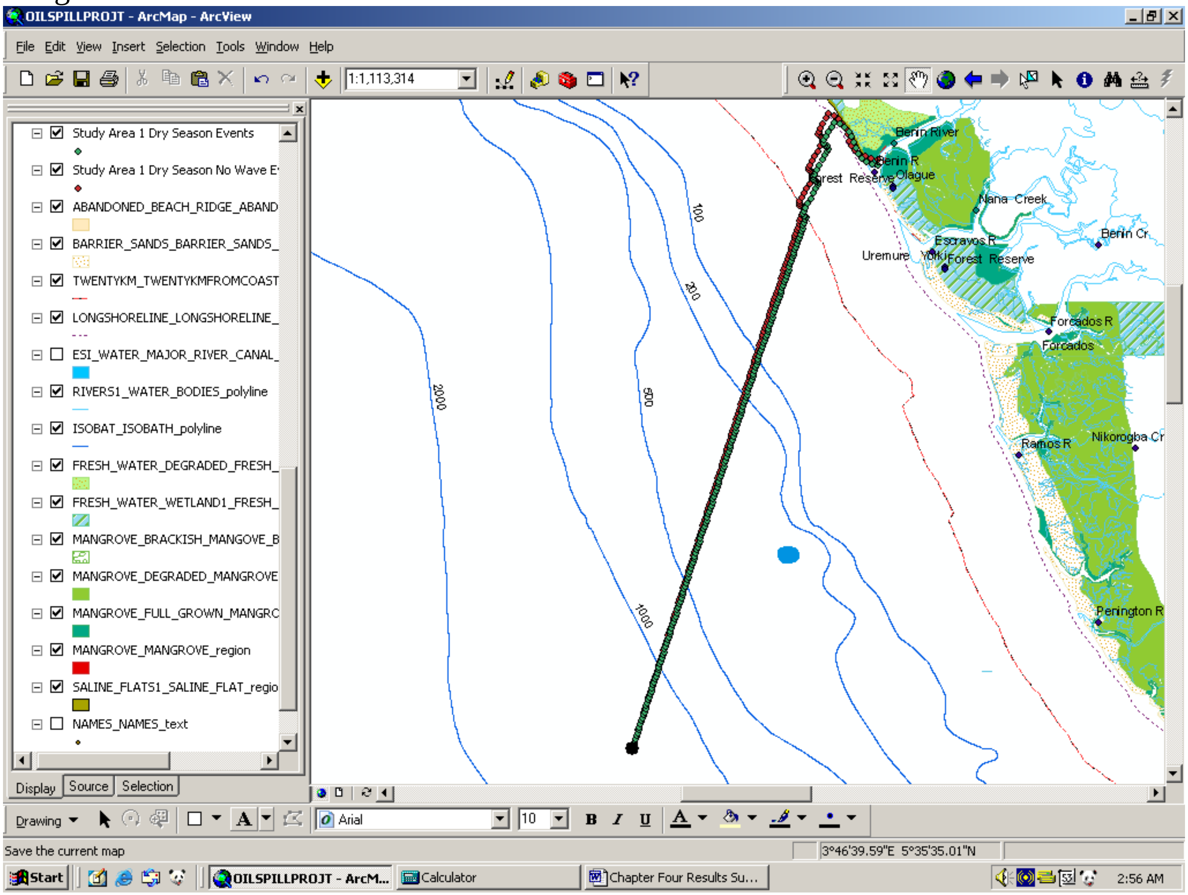

Figure 3.7: Oil Spill Trajectories for the Dry Season in Study Area I With Wave Parameters and Without Wave Parameters

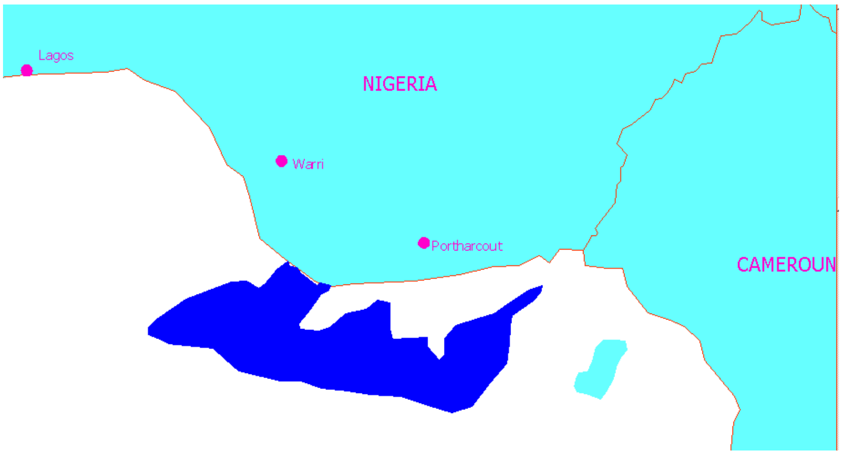

Figure 3.8: Oil Trajectory for the Worst Case Release of Oil in Wet Season

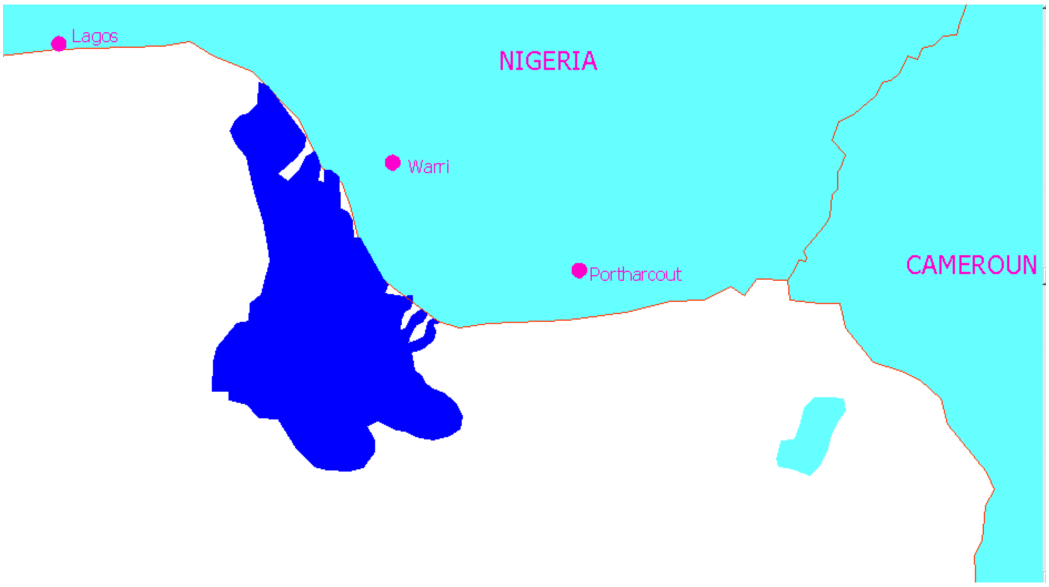

Figure 3.8: Oil Trajectory for the Worst Case Release of Oil in Dry Season

3.3 Summary of Analysis of Results

For both wet and dry seasons, the ocean current is the major factor for moving the oil spill from the Atlantic Ocean to the fairly deep waters. While the Longshore current and tides are the dominant forces moving the oil spill in shallow waters. Wind drift current and wave drift currents are secondary factors for moving the oil spill during wet and dry seasons.

The average speed of oil spill on Nigerian coastal waters is 0.29m/s in very deep waters and deep waters, 0.18 m/s to 0.48m/s in fairly deep waters and 0.31m/s to 0.71m/s along the shoreline during the wet season.

The bearing of the oil spill varies on Nigerian coastal waters during the wet season. In very deep waters and deep waters, the average bearing of the oil spill is between 83.09^o and 84.58^o. In fairly deep waters, the average bearing is 66.99^o to 135.12^o while the oil spill tend to move along the coastline along the bearing of the longshore current.

In study area I, the oil spill model indicates that 422,125.548 barrels of oil out of 560,000 spilled oil would remain after 150 hours during the wet season. This means that 24.62 percent of the oil would have evaporated by 150hours after the oil spillage. The slick area by this time would be 1656.080sq km.

In study area II, the oil spill model indicates that 439,873.638 barrels of oil out of the 560,000 spilled oil would remain after 131 hours during the wet season. This means that 21.45 percent of the oil would have evaporated by 131hours after the oil spillage. The slick area by this time would be 1708.032 sq km.

During the dry season the speed of oil spill is reduced. The speed of oil spill during the dry season is 0.21m/s to 0.22m/s in very deep waters and deep waters, 0.10m/s to 0.42m/s in fairly deep waters and 0.25m/s -0.53 m/s along the shoreline. The difference in the speed of the oil spill for both seasons is due to the fact that the speed of Guinea current (0.23m/s) which is prevalent during the wet season is higher than that of the Benguela current (0.17m/s) which is prevalent during the dry season.

The bearing of the oil spill also varies during the dry season. In very deep waters and deep waters, the bearing of the oil spill is between 16.99^o to 20.00^o. In fairly deep waters, the bearing of the oil spill is between 294.47^o to 30.95^o. In shallow waters the oil spill move in the direction of the longshore current.

During the dry season in study area I, the oil spill model indicates that 347,884.567 barrels of oil out of the 560,000 spilled oil would remain after 222hours. This means that 37.88 percent of the oil would have evaporated by 222hours after the oil spillage. The slick area by this time would be 1432.440sq km.

During the dry season in study area II, The oil spill model also indicates that 507,168.692 barrels of oil out of the 560,000 spilled oil would remain after 56hours. This means that 9.43 percent of the oil would have evaporated by 56 hours after the oil spillage. The slick area by this time would be 1900.484 sq km.

The wind drift current speed changes with changes in wind speed and water depth. The wind drift current speed increases with increase in the wind speed, decreases with decrease in water depth and is deflected by 15 degrees to the right of the bearing of the wind on Nigerian coastal waters. During the wet season, the wind drift speed is 1.79**%** of the wind speed in deep water and 0.50**%** of wind speed in shallow water. During the dry season, the wind drift speed is 1.94**%** of the wind speed in deep water and 0.61**%** of wind speed in shallow water. The increase in the wind drift speed during the dry season is due to the fact that the speed of the wind is higher during the dry season. The wind drift speed tends to zero along the coastline.

The wave drift current speed increases as one moves towards the shoreline. The speed of the wave drift current is 0.003m/s in the Atlantic Ocean, 0.004m/s in deep sea, 0.006m/s in fairly deep waters and 0.011m/s in shallow waters. The bearing of the wave drift current is 45^{o} on Nigerian coastal waters. The effects of waves is negligible in very deep waters and deep waters but cannot be dispensed with in shallow waters.

The effect of tides in very deep waters is negligible. The horizontal speed of tides in the deep sea is between 0m/s and 0.013m/s. In fairly deep waters and in shallow waters, the horizontal speed of tide on Nigerian coastal waters varies between 0m/s to 0.22m/s. The bearing of the tidal waters is 45 degrees during high waters (bearing of the wind) and 225 degrees during low waters (back bearing of the wind bearing).

Longshore current is a dominant factor for moving the oil spill in shallow waters and along the coastline. The speed of the longshore current is between 0.16m/s and 0.67m/s and move in various bearings at different parts of our coastline.

The average rate of evaporation of oil spill is 919.163 barrels of oil per hour during the wet season and 955.475 barrels of oil per hour during the dry season. The difference of 36.312 barrels of oil per hour during wet and dry season may partly be attributed to the difference in their wind speed. The wind speed is higher during the dry season. The rate of evaporation of oil spill is a function of the wind speed and exposure to sunlight.

Statistical analysis using Hotelling's T^2 indicates that the effect of adding waves parameters does not significantly affect the oil spill result. However, the accuracy of the oil spill model is improved by adding the wave parameters. Results from this work show that the incorporation of wave parameters into the oil spill model causes the oil spill to get to the shore a few hours earlier (one hour during the wet season and eight hours during the dry season for study area one) than when the wave parameters were neglected in the model. The addition of the wave parameters also gives additional insight of the additional impact the oil spill will have on coastal wetlands.

The results from the new model also indicated that oil spill would impact the same part of our coastal areas as signified by OILMAP trajectory model during the dry season.

During the wet season in study area I, the oil sensitivity index map indicates that the oil spill will pollute and destroy the barrier sands, mangrove forest, mangrove degraded areas and freshwater degraded region. The oil spill will also pollute rivers, creeks and freshwater between Kulama River and Ramos River.

During the dry season, the indication we have from the oil sensitivity index maps in study area I is that the mangrove, mangrove degraded, freshwater degraded and barrier sands would be negatively impacted by oil spill. Benin River, adjacent creeks and freshwater sources will also be polluted.

In study area II, the oil sensitivity index map indicates that during the wet season, oil spill will pollute the barrier sands and freshwater degraded region. Rivers, creeks and drinking water around Eket will also be polluted.

During the dry season in study area II, the oil sensitivity index map indicates that oil spill will destroy and pollute the freshwater degraded region, freshwater wetlands, barrier sands and abandoned beach ridges. Rivers, creeks and freshwater supplies between Eket and Imo River will also be polluted.

4. CONCLUSION AND RECOMMENDATIONS

Conclusion and recommendations based on this work are given in the following sections.

4.1 Conclusion

Some oil spill models have also been deployed to manage oil spill incidents in the country. However, little success has been achieved in previous efforts to manage oil spill incidents with these oil spill models. Lack of real time meteorological and historical data, coupled with inability to develop a model which takes into consideration the full ocean dynamics, waves, bathymetric of Nigerian coastal waters and peculiar longshore current effects along the Nigerian coastline led to the little success recorded in managing oil spill incidents on Nigerian coastal waters.

A new oil spill trajectory model has been developed in this work. The relationship and the effect of waves induced current in the transport of oil spill on water was considered in the development of the model. 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. Relevant equations for calculating the rate of spreading and evaporation of oil were also included in the oil spill model to enable the determination of the fate of oil spill.

The advantages of the model developed in this work are that it is readily available, accurate, as it has taken into consideration the major factors (including wind drift current, ocean currents, waves, tides and longshore current) that influence oil spill dispersal on coastal waters. The attribute of our basemap, which include the environmental sensitivity index maps of the country, oil blocks, oil and gas wells, bathymetry of the coastal waters and coastal towns and villages makes it unique. To cap it all, the oil spill trajectory model and the basemap are in the same ArcGIS environment and file.

4.2 Recommendations

The following recommendations if implemented will go a long way in managing and contolling oil exploitation and exploration activities in the country:

1. There is a need for a better understanding of the coastal ecology so as to evaluate the significance of the impacts generated by oil spill incidents.
2. The Federal Government in conjunction with oil parastatals and other non-governmental agencies should create more meteorological stations near the shoreline or on the coastal waters. The meteorological stations should provide real time or predicted meteorological data of the surrounding environment. This data would serve among other things as input data into oil spill models.
3. Medium scale digital maps should be made from satellite images from the Nigeria Sat-1. Images from the satellite and other satellites such as those from Radar satellites in orbit could also be used for managing oil spill incidents in the country.
4. Establishment of regional spill response centres along our coastlines, and the use of data collected with an airborne system will help in managing oil spill problems in Nigeria.
5. Geographic Information System (GIS) could also be used to identify oil spill responders and provide information about the closest resources of oil spill response equipment and personnel.
6. The petroleum industry should work closely with government agencies, universities and research centers and come out with management strategies for combating the menace of oil spill incidents.
7. More funds should be provided by all the stakeholders in the oil industry for further research in the development and use of oil spill models in the country. The adoption and improvement on the model developed in this research work and the procurement of other oil spill models would serve as a basis in carrying out more research in this area.
8. When a spill occurs, various governmental and non-governmental agencies should harness all available resources to reduce the impact of the oil spillage on our coastal environment.

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