An Improved Model for the Spread of Crude Oil Spill on Water

(A Case Study of Niger Delta Coastal Line)

[1]J.O.C. Eluma, [2]K.O. Okpala, [3]E.E. Effiong, [4]O.E. Onyelucheya

[1,2,3,4] Department of Chemical Engineering, Federal University of Technology, P.M.B. 1526, Owerri, Nigeria

Abstract: **A Mathematical model and its analytical solution that can predict the spread of crude oil spill slicks in the Niger Delta coastal line is presented. This model considers the spreading in the regime when the inertial and viscous forces counterbalance gravity and takes into account the strong effects of winds and water currents. The effective wind velocity and direction of the oil slick is resolved by the application of trigonometric principles. By applying tidal and wind velocity principle to Abowei's equation, the developed model is simulated. The knowledge of the trajectory followed by an oil slick spilled on the coastal line is valuable in the estimation of potential risks and in combating the pollution using floating barriers, detergents, etc. In order to estimate these slicks trajectories an improved model, based on mass and momentum conservation equations is needed.**

Keywords: **Spreading; Oil spill; Niger delta; Oil pollution; coastal line; wind velocity; Oil properties.**

1. INTRODUCTION

In recent years there have been an increasing concern and agitation over the growing contamination of Nigeria waterways particularly Niger delta shoreline areas caused by oil spills. The Niger Delta basin of Nigeria situates on the continental margin of the Gulf of Guinea in the equatorial West Africa between latitudes 3^{o} and 6^{o} North and longitudes 5^{o} and 8^{o} East Deltas are usually fertile, contain diverse resources and are therefore noted for large human settlements and civilizations. The Niger Delta Coastal Line is Nigeria's largest navigation corridor, it is subject to the risk of oil contamination [1]**.** With the possibility of oil spills in the system, an adequate means is needed for analyzing or predicting the movement and spreading of oil slicks.

Different analytical models have been suggested based on theoretical knowledge of the relevant processes and several semi-empirical models are available for simulation of the oil slick spreading and drifting on water, however, Fay's model on spill transport and has continued to form the base for validation of other models[2][3][4][6][9][11]]. In depth review of these models, show that Fay [6], give better prediction of extent of spread. Even though this model has a velocity term U, it represents the spreading velocity in the absence of some important local climatic factors such as wind and tide. However, in the Niger -Delta coastal line conditions are far from being totally stagnant.

A model that could predict oil spread rate to a higher degree of accuracy based on the physical characteristics of the oil and the aquatic medium, such as viscosity, density, surface tension; the volume of oil discharged into the sea; the spreading rate force and the effect of wind and tidal currents will be presented.

2. MATERIALS AND METHOD

The development of equations for determining the spread of petroleum spill and the coefficient of spread on the aquatic environment is essential for its containment [5].

2.1 Equation For Spreading Coefficient:

If a quantity of petroleum slick is introduced on a water surface at constant pressure and temperature so that at time, t =0, the petroleum is present in a monolayer of appreciable thickness, then the free surface energy of petroleum water is given by the total energy [6][7][9][13][14] as:

$$G = E - TS \quad (1)$$

Define E as the internal energy, T is the absolute temperature, and S the entrolpy.

$$dG = dE - d(TS) = (TdS\text{-}PdV) - (TdS+SdT) = -PdV - SdT \quad (2)$$

At constant temperature, **$dT = 0$; $dG = -PdV$**; where **$-PdV$** is the work done on the system. The work done in this case, is the work in forming a new surface area **da'** at constant temperature is **$\sigma da'$**, hence,

$$dG = \sigma da'; \; \sigma = dG/da' \quad (3)$$

$$dG = (\partial G/\partial a'_w)da'_w + (\partial G/\partial a'_{wp})da'_{wp} + (\partial G/\partial a'_p)da'_p \quad (4)$$

$$\text{But} \quad da'_p = da'_{wp} = -\, da'_w \quad (5)$$

Where component **w** constitutes the substrate water and **p** the spreading petroleum, and G the free surface energy Substituting equation (5) into (4), we obtain:

$$dG = (\partial G/\partial a'_w)da'_w - (\partial G/\partial a'_p)\, da'_w - (\partial G/\partial a'_{wp})\, da'_w \quad (6)$$

Thus;

$$dG = (\partial G/\partial a'_w) - (\partial G/\partial a'_p) - (\partial G/\partial a'_{wp}) \quad (7)$$

However, the surface tension of water, oil, oil-water interface can be expressed in terms of free surface energy.[7].

$$\partial G/\partial a'_w = \sigma_w; \; (\partial G/\partial a'_p) = \sigma_p; \; (\partial G/\partial a'_{wp}) = \sigma_{wp} \quad (8)$$

Hence the coefficient area **$(-\partial G/\partial a'_p)$** gives the free energy change of the spreading of a film of petroleum (p) over the water surface **(w)** and is called the spreading coefficient of p and w. Substituting Equation (8) into (7) gives: [6][7][10]

$$K_{p/w} = \sigma_w - \sigma_p - \sigma_{wp} \quad (9)$$

$K_{P/w}$ is the coefficient of spread of p on w

The surface tension of immiscible liquids such as water - petroleum, σ_{wp} is further related as:[6][7][10]

$$\sigma_{wp} = \sigma_w + \sigma_p - y^*(\sigma_w\sigma_p)^{1/2} \quad (10)$$

Substituting equation (10) and (9) gives:

$$K_{p/w} = \sigma_w - \sigma_p - (\sigma_w + \sigma_p - y^*(\sigma_w\sigma_p)^{1/2}) \quad (11)$$

$$K_{p/w} = -2\sigma + y^*(\sigma_w\sigma_p)^{1/2} \quad (12)$$

Where y* is a constant determined from field data.

The spreading rate coefficient can also be developed theoretically from the concept of adhesion and cohesion of forces as[8][10][14][19]:

$$w_{wp} = \sigma'_w + \sigma'_p - \sigma'_{wp} \quad (13)$$

and,

$$w_{pp} = 2\sigma'_p \quad (14)$$

where w_{wp} = work necessary to separate Petroleum and water (adhesion)

w_{pp} = Work necessary to assemble Petroleum (cohesion)

The spreading rate coefficient is defined by[10] as:

$$K_{p/w} = w_{wp} - w_{pp} \quad (15)$$

2.2 Spreading Rate Model:

This model is based on the integration of the mass and momentum equations along the thickness of the slick. Therefore, it takes into account the spreading of oil by itself and the transport caused by winds and water currents. As the surface tension is neglected and, therefore, only the first and second spreading regimes, i.e. gravity-inertial and gravity-viscous spreading are considered.

If we consider a single layer of petroleum slick to be spreading in the positive direction of x on a water surface If initially the water is at rest with bulk boundary stationary at x = 0.

If we consider again that z - axis is vertically downwards with z = 0 at the water surface.

Let u, w be the velocity components in the x, z, direction respectively, then the applicable time - dependent boundary layer equation for the induced flow in the water can be applied thus, [10][11]:

$$\partial \mathcal{U}/\partial t + u\partial \mathcal{U}/\partial x + w\partial w/\partial z = \mu/\rho\ \partial^2 \mathcal{U}/\partial x + (\tau^T_i - \tau^B_i - \rho g h \Delta\, \partial h/\partial x) \quad (16)$$

$$\partial \mathcal{U}/\partial x + \partial w/\partial z = 0 \quad (17)$$

$$\partial h/\partial t + U_o\ \partial h/\partial x = 0 \quad (18)$$

The horizontal force balance in the monolayer, [7][14] gives:

$$K_{p/w}\, d\sigma^*/dx + \tau_p = 0 \quad (19)$$

Where,

h = petroleum monolayer thickness, Δ is a parameter which relates the oil and water densities, $\Delta = (\rho_w - \rho_p)/\rho_w$.

μ/ρ = Kinematic viscosity of the water.

τ_p = Shear stress exerted by the water on the oil in the x - direction.

σ^* = dimensionless form of monolayer constitutive relation and is usually given[10] as:

$$\sigma^* = [\sigma_{wp} - (\sigma_p + \sigma_w)]/K_{p/w} \quad (20)$$

For $\sigma_{wp} \le \sigma^* \le 1$

Assuming a small distance dx over a short time dt, therefore for a flow velocity of u, the dimensionless surface tension, σ*, of the petroleum monolayer covered water surface at a distance dx from the point of spillage is obtained by integrating equation (19) with the known value of τ_p for this boundary layer. [6][7][10]

Thus:

$$K_x[1 - \sigma^*]dt = 0.644[\mu/\rho]^{1/2}dx \quad (21)$$

$$dx = [K^2_{p/w}/(0.644)^2\mu/\rho)dt] \quad (22)$$

$$dx = [(\sigma_w - \sigma_p - \sigma_{wp})^2 dt]/[0.4147(\mu/\rho)] \quad (23)$$

$$dx = [(W_{a'b'} - W_{b/b})^2 dt]/[0.4147(\mu/\rho)] \quad (24)$$

From equation (12) and equation (22) a development of petroleum spills spreading monolayer length, L, is obtained by integration (for x = 0 to L) over a time t, at constant velocity. [6][7][10]

$$L = [(-2\sigma_p + y^*(\sigma_w\sigma_p)^{1/2})^2 t]/[0.4147\,\mu/\rho] \quad (25)$$

The spreading coefficient, the forces of adhesion and cohesion are strongly dependent on surface tension of the fluids and viscosities. Simple regression technique were adopted. [6][7][10][12][13]

$$y^* = c_1 + c_2\sigma_p \quad (26)$$

$$y^* = 0.608 + 25.309\sigma_p \quad (27)$$

$$K_{p/w} = (0.0608 + 25.309\sigma_p)(\sigma_w\sigma_p)^{1/2} - 2\sigma_p \quad (28)$$

$$w_{a'b'} = (0.608 + 25.309\sigma_p)(\sigma_w\sigma_p)^{1/2} \quad (29)$$

The constant c_1 and c_2 are obtained as 1.284 and 0.04978 respectively,[6][12][13][14] so that:

$y^* = [1.284 \ +04978 \ (\boldsymbol{\mu}_p\rho_p)]/(\boldsymbol{\mu}_w \rho_w)$

$K_{p/w} = 1.284 + [0.04978 \ (\boldsymbol{\mu}_p\rho_p))(\sigma_w \sigma_p)^{1/2}]/(\boldsymbol{\mu}_w \rho_w) - 2\sigma_p$ (30)

$w_{b'b'} = (1.284 + [0.04978 \ (\boldsymbol{\mu}_p\rho_p))(\sigma_w \sigma_p)^{1/2}]/(\boldsymbol{\mu}_w \rho_w) - 2\sigma_p$ (31)

$\mu_w = \quad [0.04978 \ (\boldsymbol{\mu}_p \ \rho_p) \ (\sigma_w \ \sigma_p)^{1/2}]/ \ [\rho_w \ (K_{x \ b'/ \ a'} + 2 \ \sigma_p - 1.284(\sigma_w \ \sigma_p)^{1/2})]$ (32)

$L = [-2 \ \sigma_p + (1.284 + 0.04978 \ (\mu^*))^2 \ (\sigma_w \ \sigma_p)t]/ \ [0.4147 \ \mu_p\rho_p]$ (33)

Where $\mu^* = (\mu_p\rho_p)/(\boldsymbol{\mu}_w \ \rho_w)$ (34)

The model equations of [6][13][14] and equation (33) are in the nature of:

$\mathbf{L = m_1 \ t^n_1}$ (35)

Thus:

$\mathbf{Log \ L = Log \ m_1 + n_1 \ log \ t}$ (36)

The value of n, is 0.87 for each crude oil sample and volumes spilled.[13][14][15]

The value of m_1 varies with the crude oil sample and volume of spill.

$\mathbf{L = m_1 \ t^{0.87}}$ (37)

A general linear correlation model was proposed[6][13][14] as:

$\mathbf{m_1 = C_n + C_1 \ V_p}$ (38)

$\mathbf{L = \ (C_n + C_1 \ V_p) \ t^{0.87}}$ (39)

$\mathbf{L= (C_n + 0.33V_p)t^{0.87}}$ (40)

A plot of the intercept derived from equation (40) and the ratio of crude oil viscosity to $(\mu_p \ /\mu_w)$ results in the correlation.[14][19]

$C_n = - \ 1.07(\mu_p \ /\mu_w) + 11.23$ (41)

$L = [11.23 - 1.07(\mu_p \ /\mu_w) + 0.33V_p]t^{0.87}$ [14] (42)

Equation (42) is made more practicable by incorporating other functional parameters.

2.3 Improvement on the model by incorporation of Wind-induced Velocity of Spread:

The effect of wind on the velocity of spreading is considered.

Assumptions:

(a) The ambient water temperature is constant and above the pour point of oil.

(b) Oil spill moves at 3.4% of the wind speed.[16]

Let the wind velocity at time, t = 0, in a certain horizontal direction *w* on the water surface be S_w (m/s), then after a time, t, of oil spill, the velocity of the moving oil spill in this direction, (or the effective wind velocity), E_w (m/s) is given as: [16]

$E_w = 0.034S_w$ (43)

At time, t = T, after the oil spill, the total distance, L travelled by the spilled oil is given by:

$L = E_wT = 0.034S_wT$ (44)

Let A_c (m /s), be the average surface current.

If the average surface current is significant enough, the magnitude and direction of the oil spill will be determined by the resultant effect of $\mathbf{E_w}$ and $\mathbf{A_c}$

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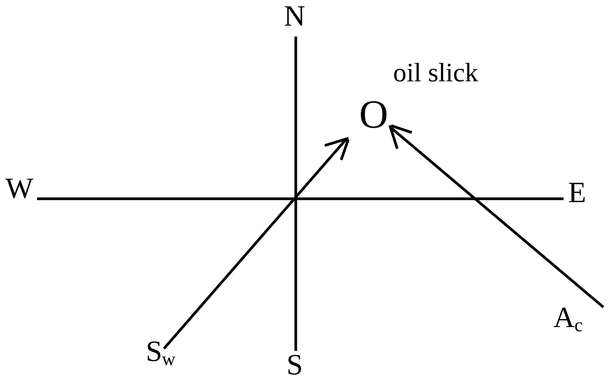

Figure.1: Illustration of wind currents

Assuming that the oil spill is moving from a South West, SW, direction with a speed of S_w.

Suppose that there is an average surface current A_c moving from the South East, SE, direction, as illustrated in figure (1). Both $\mathbf{S_w}$ and $\mathbf{A_c}$ separately have two velocity components, x and y.

To obtain the resultant of the two vectors, the components of the two velocities along the x and y directions have to be resolved as illustrated in figure (2) below:

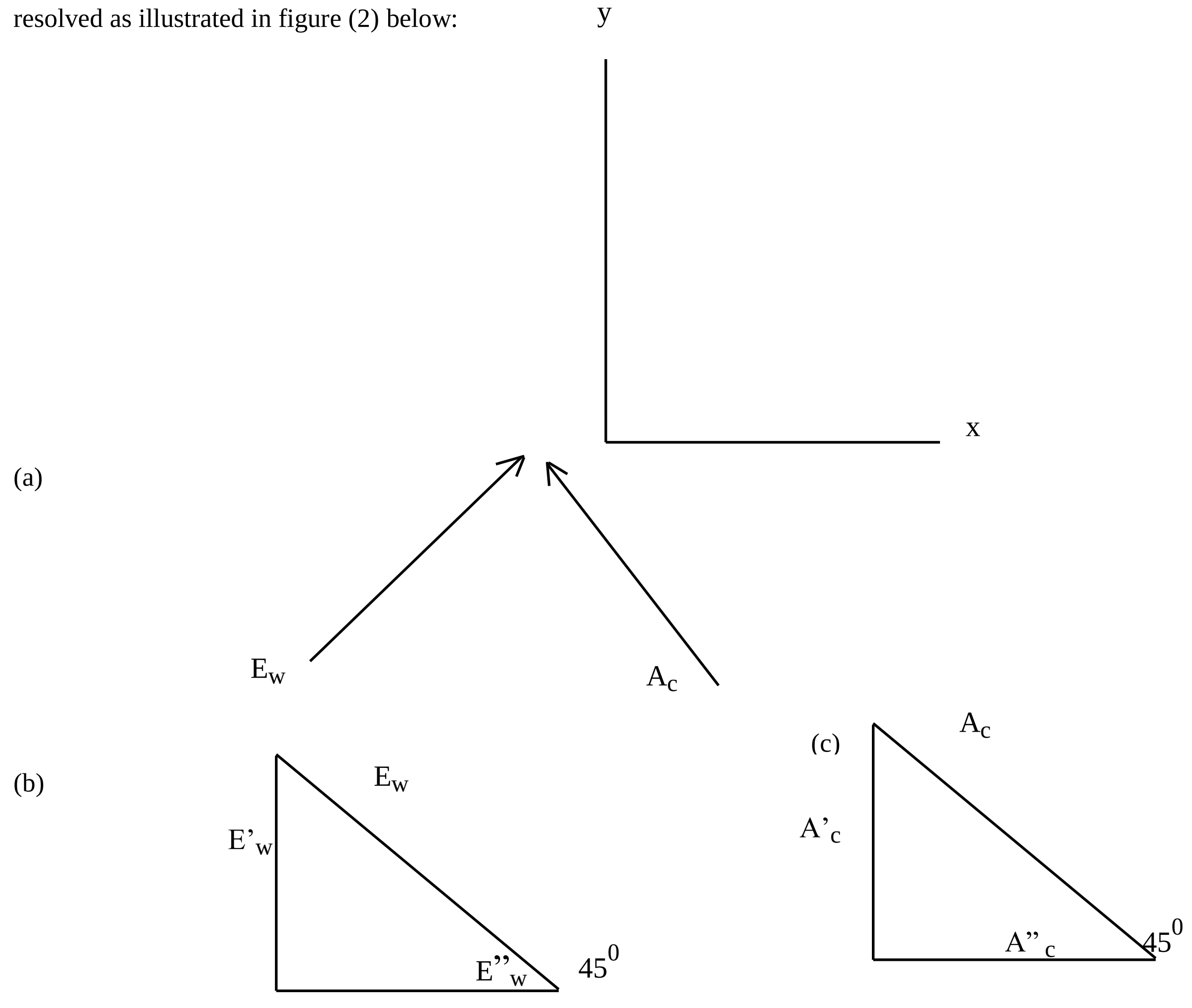

Figure.2: Illustration of velocity components

$\mathbf{E_w}$ has components $\mathbf{E'_w}$ and $\mathbf{E''_w}$, while $\mathbf{A_c}$ has components $\mathbf{A'_c}$ and $\mathbf{A''_c}$ as shown in figure (2) above. Considering figure (2)(b)

By resolving the velocity components using trigonometric applications:

$$E_w = (0.034S_w)\,Cos45^0 + (0.034S_w)\,Sin\,45^0 \qquad (45)$$

But from Pythagoras rule:

$$E_w^{\ 2} = E'_w{}^2 + E''_w{}^2 \qquad (46)$$

$$E_w^{\ 2} = ((0.034S_w)\ Cos45^0)^2 + ((0.034S_w)\ Sin45^0)^2 \qquad (47)$$

$$\mathbf{E_w} = SQRT\ \mathbf{(}((0.034S_w)\ Cos45^0)^2 + ((0.034S_w)\ Sin45^0)^2\mathbf{)} \qquad (48)$$

Similarly, considering figure (2)(c)

The vector $\mathbf{A_c}$ can be resolved into two components such that:

$$\mathbf{A_c = A'_c}\ Cos315^0 + \mathbf{A''_c}\ Sin315^0 \qquad (49)$$

The final average surface current A_c influencing the effective wind velocity is obtained as:

$$A_c = SQRT\ \mathbf{(}(A'_c\ Cos315^0)^2 + (A''_c\ Sin\ 315^0)^2\mathbf{)} \qquad (55)$$

However, the combined effect of equations (47) and (50) contribute to the significant velocity of spread of the spill. If, as envisaged earlier, that the combined effect is represented now in figure (3) below:

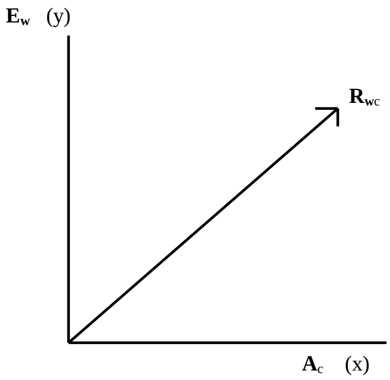

Figure.3: Illustration of combined velocities and resultant.

Let $\mathbf{R_{wc}}$ be the resultant of the two velocities, $\mathbf{E_w}$ and $\mathbf{A_c}$ moving now from an angle, θ_{wc}

$$\mathbf{R_{wc}^{\ 2} = E_w^{\ 2} + A_c^{\ 2}} \qquad (56)$$

$$R_{wc}^{\ 2} = \mathbf{(}(0.034S_w\ Cos45^0) + (0.034S_w\ Sin45^0)\mathbf{)^2} + \mathbf{(}(A'_c\ Cos\ 315^0) + (A''_c\ Sin\ 315^0)\mathbf{)^2} \qquad (57)$$

So that the velocity $\mathbf{R_{wc}}$ (m/s), is given as:

$$\mathbf{R_{wc}}\ (m/s) = SQRT\ (\mathbf{(}(0.034S_w\ (Cos\ 45^0 + Sin45^0))^2 + \mathbf{(}A_c\ (Cos315^0 + Sin315^0)^2\mathbf{))} \qquad (58)$$

Equation (58) is the velocity at which the oil spill is moving in the forward direction on the water surface at constant temperature. It is possible to have a directly opposing density current in form of drag wind velocity, $\mathbf{D_w}$, moving from the same angle as equation (58) above but in opposite direction.

The Drag wind velocity for a unit area is given as: [17]

$$D_w \quad = \quad V_p\ \tau_p E_w^{\ 1.8} \qquad (59)$$

$$\text{Where, } \tau_p = 0.029(\mu_p\mu_w)^2 \qquad (60)$$

The final wind velocity $\mathbf{U_{wc}}$ of the spread of the oil spill on the water surface under this condition can be represented by:

$$\mathbf{U_{wc} = R_{wc} - D_w} \qquad (61)$$

Hence,

$$\mathbf{U_{wc}}\ (m/s) = SQRT\ \mathbf{[}(0.034S_w\ (Cos45^0 + Sin45^0))^2 + (A_c\ (Cos315^0 + Sin315^0)^2)\mathbf{]}\ \mathbf{–}\ (0.029\ V_p(\mu_p\mu_w)^2\ E_w^{\ 1.8})^2 \qquad (62)$$

$$\mathbf{U_{wc}}\ (m/s) = [(0.0023S_w^{\ 2} + 1.4142A_c^{\ 2})^{1/2} – ((0.029V_p(\mu_p\mu_w)^2\ E_w^{\ 1.8})^2)] \qquad (63)$$

Where $\mathbf{U_{wc}}$ (m/s) is the final wind velocity

Equation (63) is greatly affected by the functional parameters of the oil, such density, viscosity, surface tension, quantity of oil spilled and the fluid regime. [11]

A directional wind is acting on the viscosity, surface tension and spreading coefficient according to the relationship: [11][18]

$$U = \{[4g(\rho_w - \rho_p)\sigma_w\sigma_p]/[3K\rho_w\mu_w]\}^{1/2} \quad (64)$$

$$\mu_w = [4g(\rho_w - \rho_p)(\sigma_w\sigma_p)/[3K\rho_w U^2] \quad (65)$$

Substituting equation into Equation (42) gives:

$$L = [11.23\text{-}\{1.07[3K\mu_p\rho_w U^2]\}/\{[4g(\rho_w\text{-}\rho_p)(\sigma_w\sigma_p)]\} + 0.33V_p]t^{0.87} \quad (66)$$

Assuming that:

(a) The slick is one continous layer floating on the water surface.

(b) Physical and Chemical changes such as evaporation are neglected.

(c) The only change that the spill can undergo is movement from one place to another.

$$L= [11.23\text{-}\{1.07[3K\mu_p\rho_w U_{wc}^{\ 2}]\}/\{[4g(\rho_w\text{-}\rho_p)(\sigma_w\sigma_p)]\}+ 0.33V_p]t^{0.87} \quad (67)$$

Where U_{wc} is the final wind velocity

By substituting Equation (63) in Equation (67) gives:

$$L = \frac{[11.23\text{-}1.07[3K\mu_p\rho_w[(0.0023S_w^{\ 2} + 1.4142A_c^{\ 2})^{1/2} - ((0.029V_p(\mu_p\mu_w)^2\, E_w^{\ 1.8})^2)^{1/2}]}{[4g(\rho_w\text{-}\rho_p)(\sigma_w\sigma_p)] + 0.33V_p]t^{0.87}} \quad (68)$$

The oil spill will be moving in the direction, θ_{wc}, such that

$$\tan\theta_{wc} = (A_c\,(\mathrm{Cos}315^0 + \mathrm{Sin}315^0))/(0.034S_w\,(\mathrm{Cos}45^0 + \mathrm{Sin}45^0)) \quad (69)$$

$$\theta_{wc} = \tan^{-1}\ (1.4142A_c)/\ (0.0481S_w) \quad (70)$$

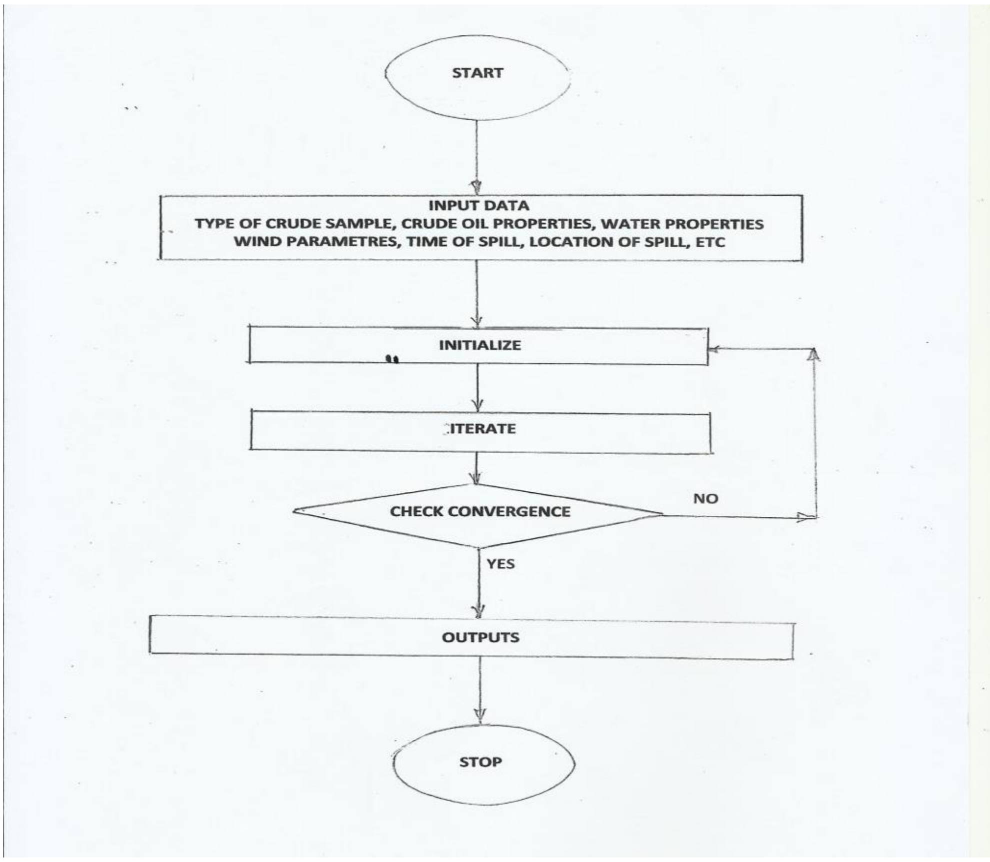

Figure.4: Computer Simulation Flow Chart

3. RESULTS AND DISCUSSIONS

In this work, computer simulation has been used to obtain useful output. The first step in validating a model is to compare with available analytical solutions. For this problem the semi analytical solution of Fay are adequate. Physical validation requires field measurements. Figure (11) reveals that the results obtained from the computation of the developed predictive empirical model compared well with those obtained from the experimental investigation and Fay's gravity-viscous spreading regime model.

The major difference of this model, as compared to other used semi-empirical models, is that this model is more generalized by the inclusion of other functional parameters (shear stress, surface tension, density and viscosity of the oil spilled, the aquatic environment, final wind velocity and the spreading force). This feature increases compatibility of the oil spill model with the modern hydrodynamics, meteorological and ecological models. Another advantage of the model lies on the use of only physically relevant parameters whenever possible to increase a range of model application for different spill scenarios and environmental conditions. While Fay [6], based his work on correlation and regression technique, the present work was based on computer simulation which is cheaper in the long run and easier to implement.

Figure (5) show the computational domain. Figures (6) and (7) show the comparison between the time history records computed adopting Fay's model and tide table data. It is observed that the spread length (water surface) and current from tidal analysis are in good agreement with the tide table data.

From figure (8), it can be observed that the oil slick moves on the water surface without disintegration during the first day, on the second day some slicks are broken and become smaller patches figure (9) three or four days later, more and more oil patches spread, figure.(10)[6][14]

From the relationships of the model equations, it is important to note that the extent of spread, especially on wind induced environment is dependent on the physical properties of petroleum and the aquatic environment, the quantity of petroleum spilled and the final wind velocity occasioning the spread.

The spreading coefficient remains constant with change in time and surface wind velocity, S_w. The surface wind velocity obviously affects the distance of spread and kinematic momentum rate but does not affect the final velocity significantly. The final velocity and distance is affected by the area. A change in the average surface current has great effect on the velocity and distance.

It is noted that the difference between the values forward spill velocity R_{wc}, and final velocity, U_{wc}, are negligible, apparently because the drag wind velocity itself is also negligible.

This improved oil spill model can be used to assess the expected fate of Nigeria light crude oil that may be spilled during oil operations in Niger delta Coastal water. It can be used to critically assess the fate of oil released during any scenario:

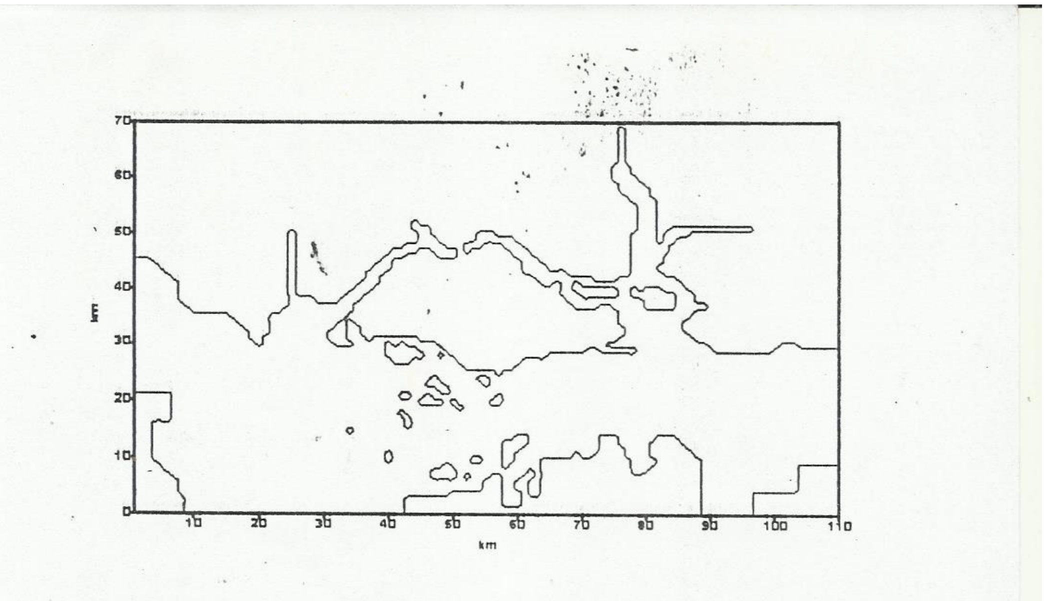

Figure.5: Computational domain.

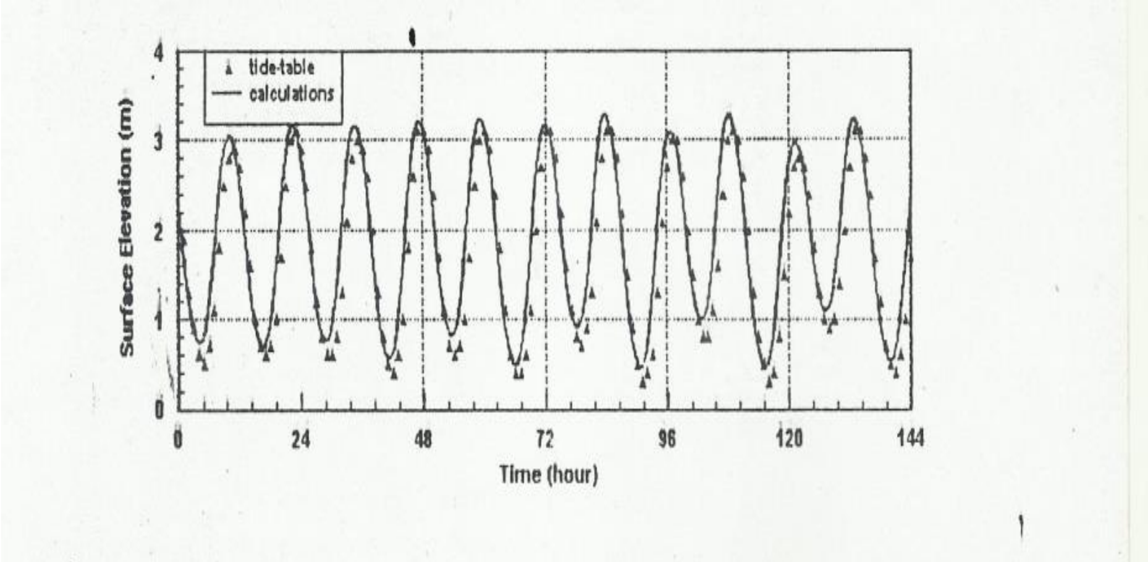

Figure.6: Time history of surface elevation

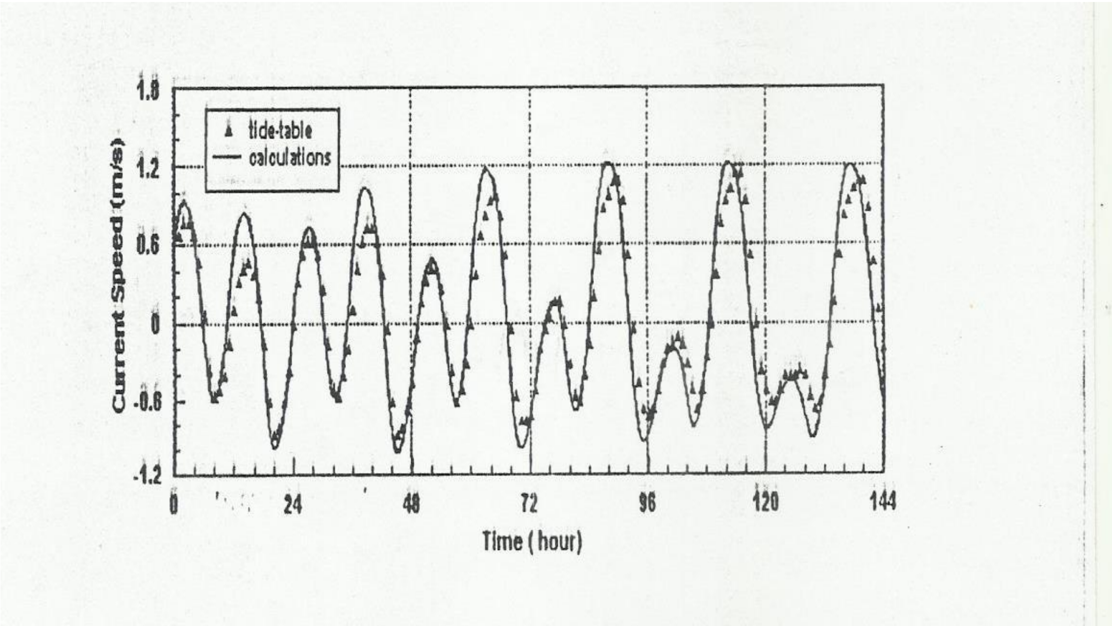

Figure.7: Time history of surface layer current.

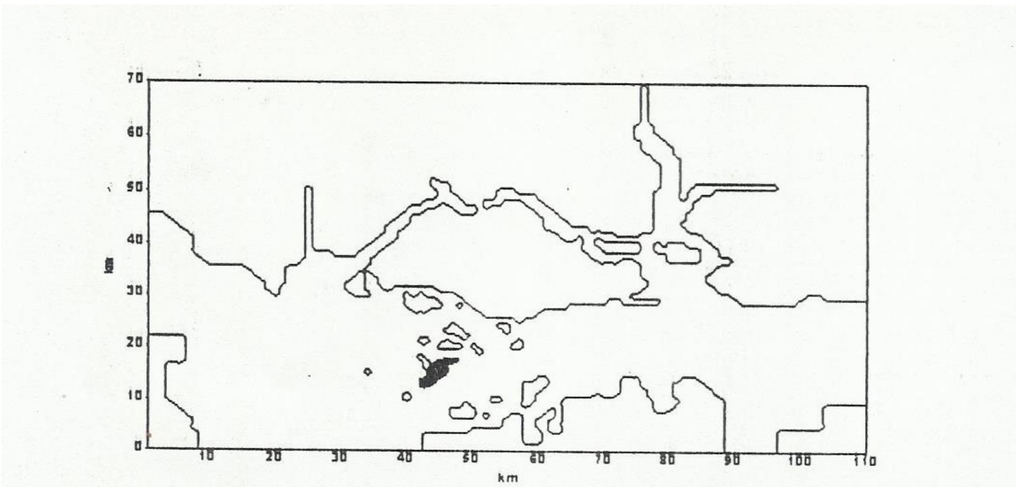

Figure.8: Oil slick spreading on water surface (17 hours after spill)

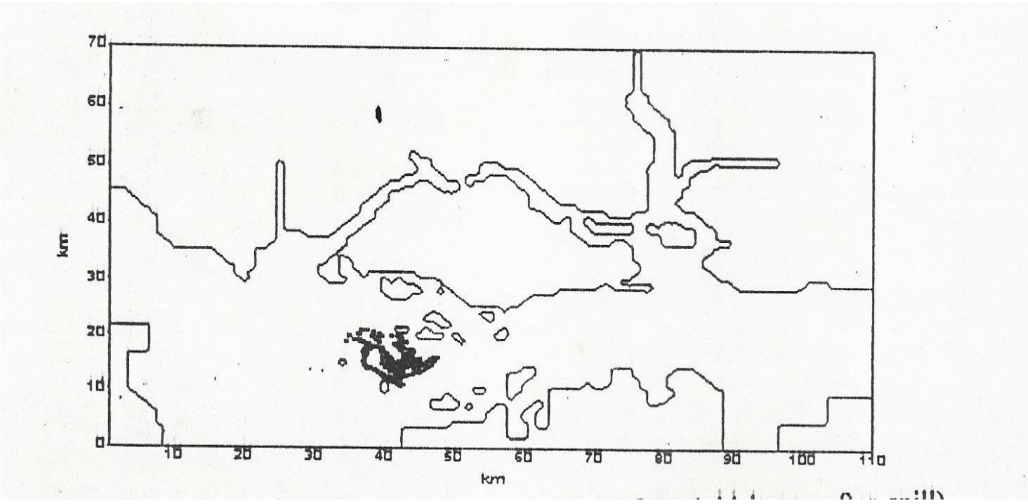

Figure.9: Oil slick spreading on water surface (44 hours after spill)

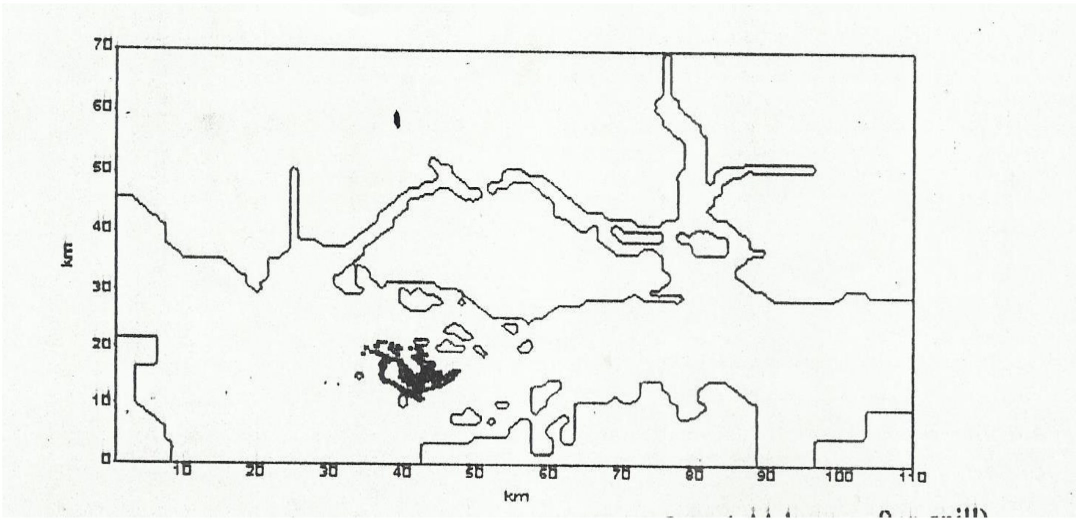

Figure.10: Oil slick spreading on water surface (69 hours after spill)

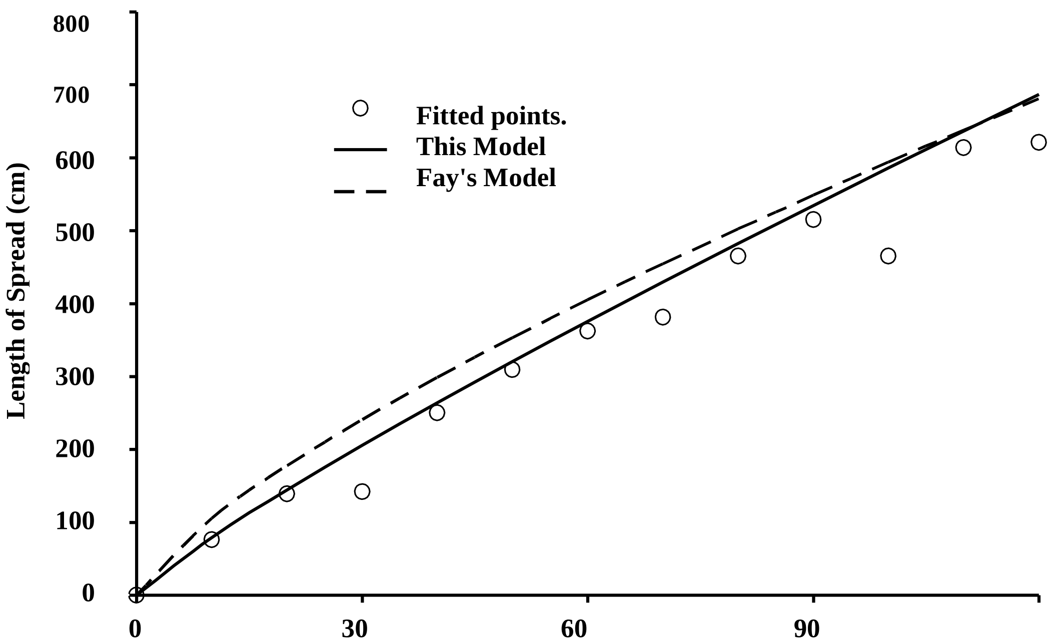

Figure.11:Comparison of experimental determined Extent of Spread, Fay's Model and the Developed Model for Predicting the Extent of Spread

4. CONCLUSION

The need for analysing or predicting the movement of spilled oil slick, arose due to growing concern over the increasing contamination of water bodies in our environment especially along the Niger Delta coastal lines. This is because any oil spill has a devastating and obvious effect on marine ecology. Crude oil when spilled on water commences various processes including spreading, and if unchecked and uncontrolled, can cause great environmental destruction to the affected areas.

This paper presented a mathematical and numerical model to predict oil spill movements in the sea. Results for the spreading in the calm water were compared with semi-analytical solutions and the agreement was good. Although there are no benchmark solutions available for the case where the water moves, the results for a general problem, where the water moves periodically in time, follow the expected physical trends and the mass centre of the slick moves with the water current velocity[14]

The result from the model compares well with the laboratory data and the works of Fay.

The model can be used to simulate oil spills in order to assist pollution combat tasks in the Niger delta coastal line, so it is an important tool in any oil spill contingency plan.

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