*Asian Journal of Water, Environment and Pollution*, Vol. 5, No. 3, pp. 49-55.

# Spreading of Niger Delta Oil Spill on Placid Aquatic Medium

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*Received July 24, 2006; revised and accepted October 15, 2007*

**Abstract:** Continuous research in the development of suitable predictive model is vital as the input of oil spills into the aquatic environment, particularly in the Niger Delta area of Nigeria, is alarming due to frequent oil spills. This eventually affects aquatic organisms and shoreline activities. This work developed an empirical expression that can describe the horizontal spreading of Niger Delta Oil Spills (NDOS) on a placid water body using simple physical coefficients of the oil and the aquatic medium. The empirical expression developed is a function of the spreading coefficient which was derived from heuristic arguments and enhanced to deal with gravity, viscous and surface tension forces. The extent of spread of various oil samples was found to correlate with non-dimensional groups comprising the ratios of the product between density, viscosity for oil and water respectively. This model provides an easy means to estimate oil slick transport under stagnant water conditions at specific locations in the Niger Delta area. The semi-empirical model is verified against most popular empirical model.

**Key words:** Spreading, oil spill, Niger delta, aquatic medium, oil pollution, calm water, oil properties.

## Introduction

The Niger Delta as defined by Nigerian Government extends over about 70,000 km$^2$ and makes up 7.5% of Nigeria's land mass. It includes land in Abia, Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Imo, Ondo and Rivers States. These states produce the oil and natural gas that make up to 75% of Nigerian foreign exchange earnings. The exploration of the petroleum results in oil spillage with attendant pollution problems. Niger Delta Oil Spills (NDOS) has received growing attention by scientists and environmentalists, over the past decades, as a consequence of a number of accidents (operational discharges, accidental discharges, blow-out of offshore oil wells, or when a pipeline breaks, ship wreckages, sabotage, etc.) involving the release of large amounts of oil in Niger Delta water bodies (Abowei, 1996; Njobuenwu et al., 2005).

According to reviews on the state-of-the-art in the oil spill simulation (Huang, 1983; Spaulding, 1995; ASCE, 1996; Reed et al., 1999), spreading is one of the most significant processes during the early stages of an oil spill in water, increasing the overall surface area of the oil slick, thereby enhancing mass transfer via the evaporation and dissolution processes. Gravity and surface tension promote the spreading of oil on a calm sea surface while inertia and viscosity retard spreading (Fay, 1969, 1971). Fay (1969) identified the basic mechanisms in the mechanical distribution of oil on the aquatic surface using a simple one-dimensional model and illustrated three regimes (gravity-inertia, gravity-viscous, surface tension-viscous) in the spreading of initially concentrated volumes of oil on a calm sea by dimensional analysis.

In order to predict the spreading of NDOS discharged into a placid aquatic environment, a new comprehensive empirical model, based on the physical characteristics of the oil and the aquatic medium, such as viscosity,

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density, surface tension; the volume of oil discharged into the aquatic environment; and the spreading rate force is presented. The model considers the spreading in the regime when the inertial and viscous forces counterbalance gravity.

## Experimental

An experimental system illustrated in Figure 1 is designed and assembled for the investigation of spreading of raw Niger Delta oil samples on a placid water surface. The experimental setup includes a laboratory open water channel measuring 500 cm in length, 8 cm in width and 145 cm in depth in which a measuring tape is mounted. At the end of one side of the water channel there is an oil dam in the form of a funnel of radius 2.5 cm. The channel is initially filled with fresh water obtained from Nun River in Niger Delta of Nigeria and left for about 30 minutes in order to ensure a stagnant water surface. The oil dam containing a predetermined quantity of raw Nigeria samples was gently withdrawn to enable the oil slick to spread over the stagnant water surface. The spreading of each oil sample was determined with the aid of a stop watch and tape measure.

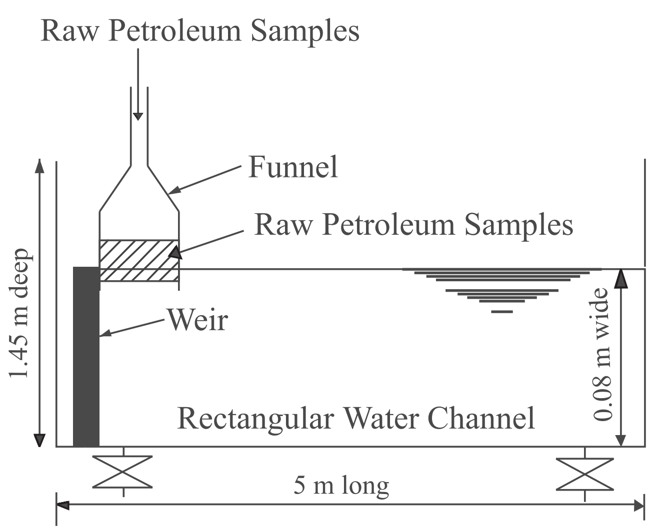


**Figure 1: Schematic diagram showing the Laboratory Open Channel for the determination of spreading of Niger Delta Oil Spills on placid aquatic medium.**

The experiment was repeated several times with a varying volume of spill. It is believed that a major component of a spill model's precision lies in accurate measurement of the physical properties of the oil and water. Hence, we performed a number of laboratory analyses on the crude oil samples and the river water to generate the parameters necessary for our model to confidently calculate oil spill behaviour. Modified ASTM methods for testing density, viscosity and surface tension of both water and three blends of Niger Delta of Nigerian oil samples from various flow stations (pipeline locations where crude oil from wells in the field are gathered before they are sent to processing) were used (Njobuenwu, 2004). The oil was mixed at varying proportion to obtain three samples with varying physical properties of interest.

**Nomenclatures**

| | |
|---|---|
| $A$ | Surface of area |
| $G$ | Free surface energy |
| $K, f, \Phi, \beta$ | Arbitrary constants used in equations |
| $m$ | Pre-exponential constant |
| $n$ | Power law exponent |
| $P$ | Pressure |
| $R(t)$ | Extent of spread |
| $S$ | Spreading Coefficient; entropy |
| $t$ | Time |
| $T$ | Absolute temperature |
| $U$ | Internal energy |
| $V$ | Volume of oil spilled |
| $\alpha$ | Constant and is determined experimentally |
| $\rho$ | Density |
| $\mu$ | Dynamic viscosity |
| $\gamma$ | Surface tension; free energy per unit area |

Subscripts

| | |
|---|---|
| $C$ | Coefficient |
| $o$ | Oil |
| $R$ | Ratio |
| $w$ | Water |

## Results and Discussion

The experimental results for selected physical properties of the oil samples and water are shown in Table 1. The result from the spreading experiment is shown in Figure 2. The figure shows a sample of experimental measurement for oil sample I spreading on placid aquatic

**Table 1: Properties of oil samples at room temperature**

| *Oil Samples* | *Density ($g/cm^3$)* | *Viscosity (g/cm.s)* | *Surface Tension of oil ($g/s^2$)* | *Surface Tension of oil/ water ($g/s^2$)* |
|---|---|---|---|---|
| Sample I | 0.88053 | 0.063833 | 38 | 29 |
| Sample II | 0.8751 | 0.027944 | 31 | 38 |
| Sample III | 0.9 | 0.071667 | 39 | 28 |
| Fresh water | 0.997 | 0.011667 | 74 | - |

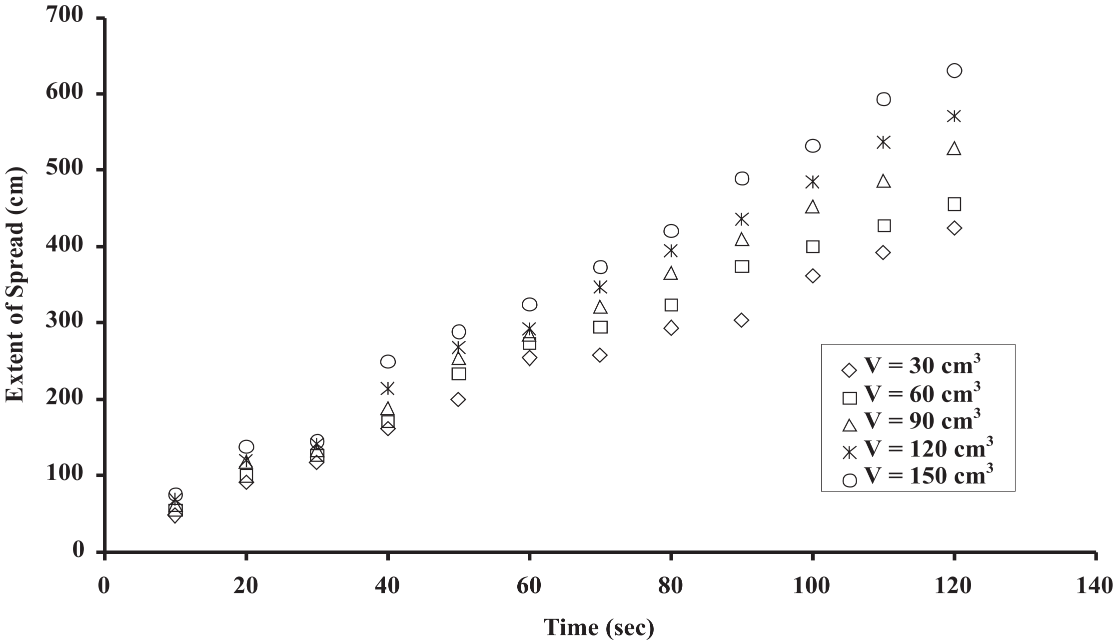


**Figure 2: Extent of spread - Time graph for Oil Sample I spilled on water at various volumes.**

regime. Similar graphs were plotted for oil samples II and III and the fitted parameters obtained were used in the formulation of the model. Those graphs were intentionally omitted to avoid redundancy of the figures since they behaved similar to Figure 2.

From the experimental results shown in Figure 2, the extent of spread $R(t)$ obeyed the power law with respect to time as follows:

$$R(t) = mVt^{n} \tag{1}$$

where $t$ is time, $n$ is the power law exponent while $m$ is the pre-exponential constant; and $V$ is volume dependent constants for each of the oil samples used. The values of $n$ and $m$ were fitted parameters by regression technique using data in plotted graphs. The exponent $n$ was deduced from the results to be independent of oil sample and volume and is approximately 0.87. The value of $m$ varies linearly with different oil samples and volume of oil spilled $V$ on the water surface.

A plot of $m$ against volume of oil spilled $V$ was made for each oil sample in Figure 3. The graphs were observed to be linear with similar slope of ≈ 0.33 at varying intercept. Therefore, from Figure 4, a general correlation model is proposed.

$$m = K + \Phi V \tag{2}$$

The following results in the form of equation (2) were obtained for the three oil samples investigated:

$$\begin{aligned} &\text{Sample I:} && m = 8.61 + \tfrac{1}{3} V \\ &\text{Sample II:} && m = 5.24 + \tfrac{1}{3} V \\ &\text{Sample III:} && m = 2.30 + \tfrac{1}{3} V \end{aligned} \tag{3}$$

The value of $\Phi$ was evaluated to be approximately 0.3333 while $K$ was observed to vary with oil properties. The magnitude of $K$ varies with the ratio of the viscosity of the oil sample to that of the aquatic environment, $\mu_R$. Thus,

$$\mu_R = \frac{\mu_o}{\mu_w} \tag{4}$$

Using linear regression, the computation gives a linear relationship with *R-Square* value > 0.99 of the form:

$$K = \beta + f\ \mu_R \tag{5}$$

The data obtained as seen in Figure 4 show that $\beta$ = 11.23 and $f$ = –1.07. Substituting equation (5) into equation (2) and further substitution of the result into (1) gives

$$R(t) = (\ \beta + f\ \mu_R + \Phi\ V)t^{n} \tag{6}$$

On substitution of the values and constants gives the extent of spread as:

$$R(t) = \left[11.23\ \ -1.07\left(\frac{\mu_o}{\mu_w}\right) + \tfrac{1}{3}\ \ V\right]\ t^{\,0.87} \tag{7}$$

Equation (7) does not contain the spreading force of the spreading oil which is the first parameter to characterise the fate of the first weathering process (Njobuenwu, 2004). This parameter determines whether the oil will spread once discharged into the sea. A positive spreading rate force signifies the oil will spread and vice versa (Adamson and Gast, 1997).

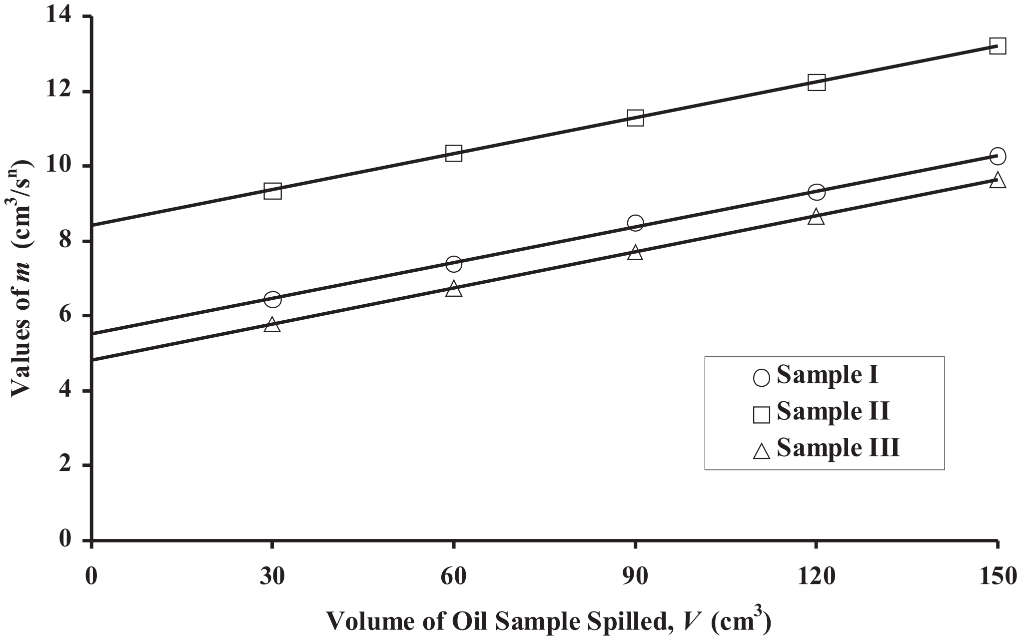


**Figure 3: Relationship between *m* in Equation (2) and volume of oil spilled on water.**

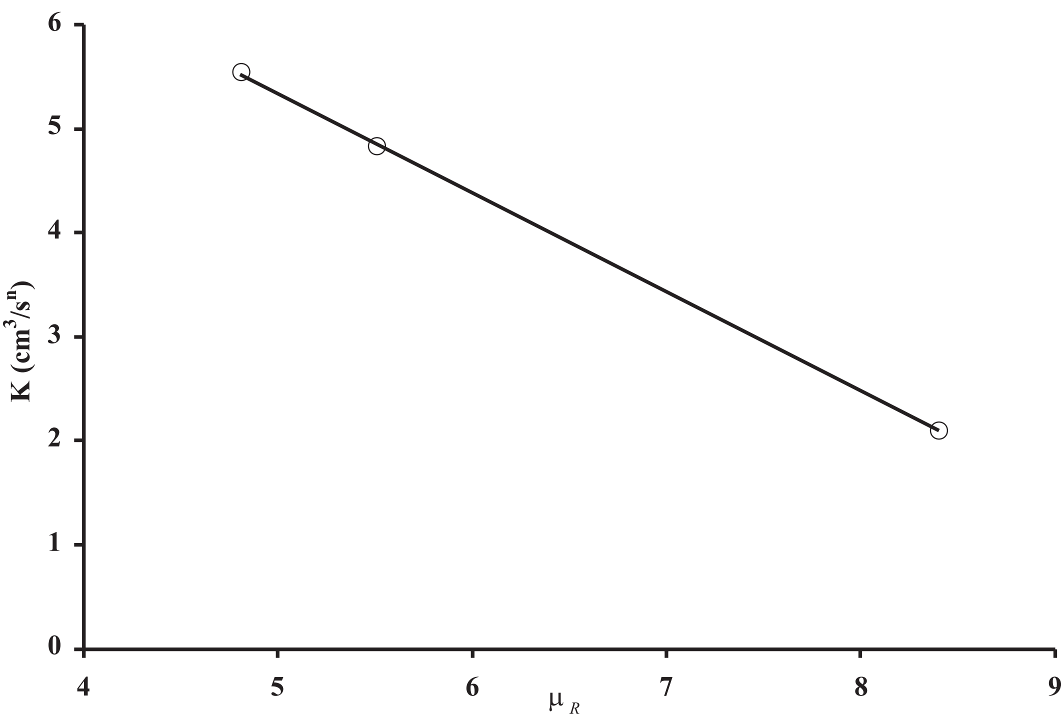


**Figure 4: *K* dependence on the ratio of viscosities, $\mu_R$, Equation (5).**

If a quantity of raw oil slick is placed on an aquatic surface at constant pressure and temperature, so that initially oil is present on a monolayer of appreciable thickness, then the free surface energy $G$ is given as:

$$G = U - TS, \tag{8}$$

where $U$ is the internal energy, $T$ is the absolute temperature, and $S$ is the entropy.

$$dG = dU - d(TS) = (TdS - PdV) - (TdS + SdT)$$
$$= -PdV - SdT \tag{9}$$

At constant temperature, $dT = 0$; then, $dG = -PdV$; where $-PdV$ represents the work done on the system (it is only one kind of work, but stands here for them all, everything but heat). In the present case, the work in making new surface of area $dA$ at constant temperature is, $\gamma dA$, thus,

$$dG = \gamma dA;\ \gamma = \frac{dG}{dA} \tag{10}$$

$\gamma$ is the free energy per unit area of new surface. Dimensionally, this is erg/cm$^2$, dyne/cm $nN/m$ or g/s$^2$. For the air-water, air-oil and oil-water interfaces, therefore, the total energy is given as (Adamson and Gast, 1997):

$$dG = \left(\frac{\partial G}{\partial A_w}\right)dA_w + \left(\frac{\partial G}{\partial A_{ow}}\right)dA_{ow} + \left(\frac{\partial G}{\partial A_o}\right)dA_o \tag{11}$$

$$dA_o = dA_{ow} = -dA_w \tag{12}$$

where the subscripts $w$ and $o$ represent the substrate (water) and the spreading oil respectively. Substituting equation (12) into (11), gives:

$$dG = \left(\frac{\partial G}{\partial A_w}\right)dA_w - \left(\frac{\partial G}{\partial A_{ow}}\right)dA_w - \left(\frac{\partial G}{\partial A_o}\right)dA_w \tag{13}$$

Simplifying equation (13) gives:

$$\frac{\partial G}{\partial A_w} = \left(\frac{\partial G}{\partial A_w}\right) - \left(\frac{\partial G}{\partial A_o}\right) - \left(\frac{\partial G}{\partial A_{ow}}\right) \tag{14}$$

The surface tension of water, oil and oil-water interface respectively is expressed in terms of free surface energy in form of equation (5) as (Adamson and Gast, 1997):

$$\left(\frac{\partial G}{\partial A_w}\right) = \gamma_w; \left(\frac{\partial G}{\partial A_o}\right) = \gamma_o; \left(\frac{\partial G}{\partial A_{ow}}\right) = g_{ow}, \tag{15}$$

Substituting equation (15) into (14) gives spreading coefficient $S_C$ as determined from the free surface energy as:

$$S_C = \frac{dG}{dA_w} = \gamma_w - \gamma_o - \gamma_{ow} \tag{16}$$

Surface tension of immiscible liquids (oil-water) $\gamma_{ow}$ is given as (Susu et al., 1997):

$$\gamma_{ow} = \gamma_w + \gamma_o - \alpha \ (\gamma_w \gamma_o)^{1/2} \tag{17}$$

Substituting equation (17) into (16), gives:

$$S_C = -2\gamma_o + \alpha \ (\gamma_w \gamma_o)^{1/2} \tag{18}$$

where $\alpha$ is a constant and is determined experimentally. Equation (18) expresses the spreading coefficient $S_C$ in terms of oil and aquatic environment surface tensions. To incorporate other factors, the constant $\alpha$ in equations (17) and (18) is determined by fitted parameters from experimental data using the physical properties of three Niger Delta of Nigerian oil samples and fresh water shown in Table 1. From Figure 5, $\alpha$ is determined as

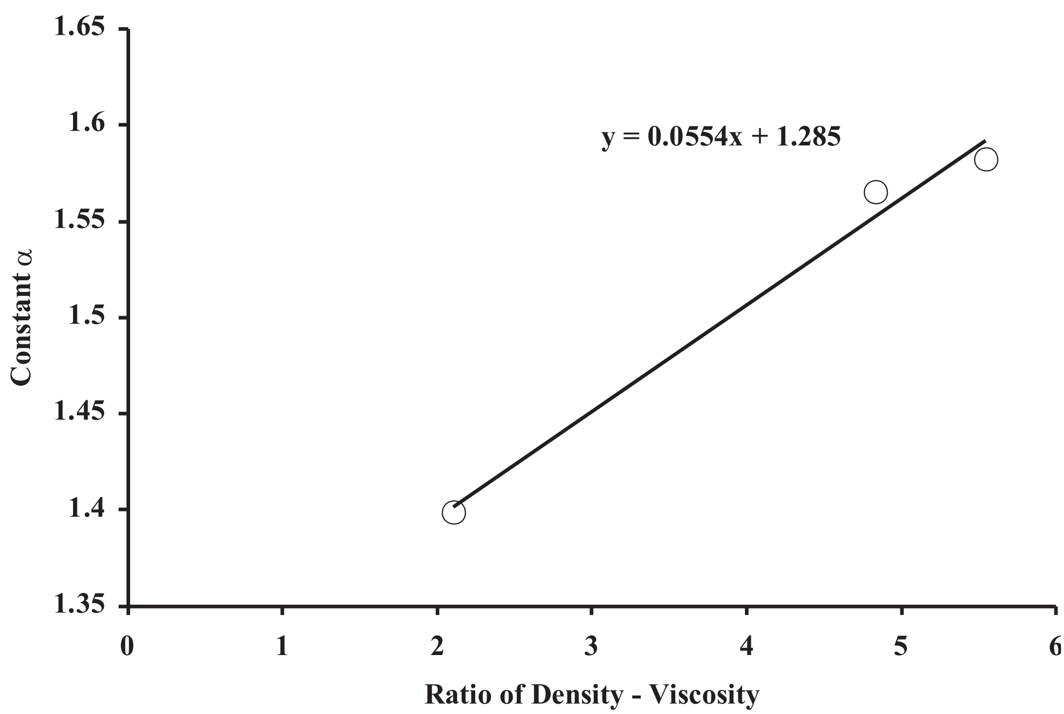


**Figure 5: Relationship between constant α and the ratio of densities – Viscosities, Equation (11).**

$$\alpha = 1.285 + 0.05539\left(\frac{\rho_o \mu_o}{\rho_w \mu_w}\right) \quad (19)$$

$\alpha$ in equation (19) compared well with the experimental values as shown in previous work [14]. Substituting equation (19) into (18) yields:

$$S_C = \left[1.285 + 0.05539\left(\frac{\rho_p \mu_p}{\rho_w \mu_w}\right)\right](\gamma_w \gamma_o)^{1/2} - 2\gamma_o \quad (20)$$

From equation (12),

$$\mu_w = \frac{0.05539 \; \rho_o \mu_o (\gamma_w \gamma_o)^{1/2}}{\left(S + 2\gamma_o - 1.285(\gamma_w \gamma_o)^{1/2}\right)\rho_w}$$

Substituting the last equation into (7) yields

$$R(t) = \left[\begin{matrix} 11.23 - 1.07 \\ \left(\dfrac{S + 2\gamma_o - 1.285 \; (\gamma_w \gamma_o)^{1/2}}{0.05539 \; (\gamma_w \gamma_o)^{1/2}}\right) + 1/3\, V \end{matrix}\right] t^{0.87} \quad (21)$$

Equation (21) is the new comprehensive empirical model for the prediction of the spreading of a finite quantity of oil spill on a placid aquatic medium.

It can be noted based on the experimental values of the oil samples and fresh water in Table 1 that using Equation (16) the oil samples has a positive spreading force so the oil will spread on the water phase due to surface tension forces. A negative value would indicate that the oil will not spread by surface forces on water (Clark and MacLeod, 1977). A significant observation shows that the extent of spread at constant volume is dependent on oil properties. This characteristic behaviour is more remarkable with viscosity variation. The oil sample II with smaller viscosity exhibited higher extent of spread. As the crude oil spreads, it quickly loses its volatile and water-dissolved components, and the remaining viscous fractions retard the spilling process; thus, the specific gravity of an oil spill can increase as the lighter substances within the oil evaporate. The higher the oil's surface tension, the more likely a spill will remain in place. If the surface tension of the oil is low, the oil will spread even without help from wind and water currents. Because increased temperatures can reduce a liquid's surface tension and viscosity, oil is more likely to spread in warmer waters than in very cold waters. The analysis shows that the oil sample II with lower surface tension spreads faster than others at the same condition.

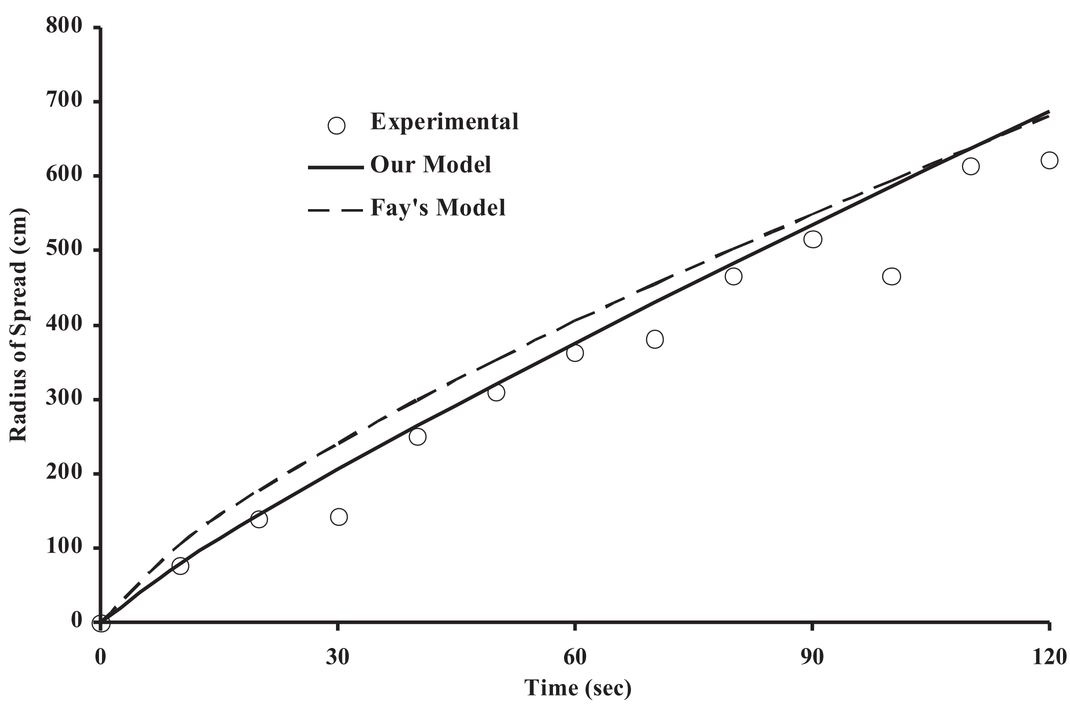


**Figure 6: Comparative analysis of experimental determined length of spread, Fay's model and the developed model for predicting the length of spread.**

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. As was already mentioned, Fay's results describe the spreading of an instantaneous spill in calm waters. Figure 6 reveals that the results obtained from the computation of the developed predictive empirical models compared well with those obtained from the experimental investigation and Fay's gravity-viscous spreading regime model (Fay 1971). The major difference of this model, Equation (21), as compared to other used semi-empirical models, is that this model is more generalized by the inclusion of other functional parameters (surface tension, density and viscosity of the oil spilled and the aquatic environment and the spreading force). This feature increases compatibility of the oil spill model with the modern hydrodynamics and ecological models. Another advantage of the model lies on a tread to use only physically relevant parameters whenever possible to increase a range of model application for different spill scenarios and environment conditions.

## Conclusion

The study has focussed on the sensitive parameters that may directly or indirectly influence environmental evaluations relating to the spread of an oil spill in water for biological, social and economic effects. The result of this work is applicable to one-dimensional spreading of oil spill in stagnant water body. The result from the model compares well with the laboratory data and the works of Fay as shown in Figure 6. Efficiency of the empirical algorithms proposed here for predicting pollutant transport can be greatly enhanced if the sensitive independent parameters are correctly utilized and measured and if the water is at quiescent conditions. The sensitive independent parameters include physical properties of oil spills, aquatic environment and the quantity of a spill.

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# Calendar of Events

**Flood Recovery Innovation and Response (FRIAR) 2008**
2 to 3 July 2008
London, United Kingdom
Website: http://www.wessex.ac.uk/conferences/2008/friar08/index.html
Contact name: Alice Jones
Organized by: University of Wolverhampton, UK, and Wessex Institute of Technology

**The International Conference on Sustainable Agriculture for Food, Energy and Industry 2008**
2 to 6 July 2008
Sapporo, Hokkaido, Japan
Website: http://www.sgp.hokudai.ac.jp/ICSA2008/
Organized by: International Council for Sustainable Agriculture Sustainability Governance Project, Hokkaido University

**Environmental Education up the Track: Hot Topics for our Community**
9 to 12 July 2008
Darwin, Australia
Website: http://www.cdu.edu.au/ehs/AAEE/
Contact name: Kiera Petrie
Organized by: Australian Association for Environmental Education

**The Mathematics of Water Supply & Pricing**
14 to 16 July 2008
Surfers Paradise, Queensland, Australia
Website: http://www.amsi.org.au/water.php
Contact name: Parvin Ahadi
Organized by: Australian Mathematical Sciences Institute

**Coast to Coast 2008**
18 to 22 August 2008
Darwin, Northern Territory, Australia
Website: http://www.coast2coast.org.au
Contact name: Narelle Hall

**Fourth International Symposium on GIS-Spatial Analyses in Fishery and Aquatic Sciences**
25 to 28 August 2008
Rio de Janeiro, Brazil
Website: http://www.esl.co.jp/Sympo/4th/index.htm
Contact name: Tom Nishida
Organized by: Fishery-Aquatic GIS Research Group

**Bies'08 Blacksea International Environmental Symposium**
25 to 29 August 2008
Gýresun, Turkey
Website: http://www.jieas.com/bies08
Contact name: Dr. ÞÜKRÜ DURSUN
Organized by: Selcuk University, Enviroment and Forestry, Giresun Governorship, Giresun Municipality

**The 12th International Conference on Integrated Diffuse Pollution Management (DIPCON 2008)**
25 to 29 August 2008
Khon Kaen, Thailand
Website: http://www.envicenter.com/iwa2008
Contact name: Erico Saito
Organized by: Research Center for Environmental and Hazardous Substance Management

**11th International River Symposium**
1 to 4 September 2008
Brisbane, Queensland, Australia
Website: http://www.riversymposium.com
Contact name: Carla Mathisen
Organized by: Major Brisbane Festivals

**The Second IASTED Africa Conference on Water Resource Management (AfricaWRM 2008)**
8 to 10 September 2008
Gaborone, Botswana
Website: http://www.iasted.org/conferences/home-604.html
Contact name: IASTED
Organized by: IASTED

**SWRM'08 - 5th International Conference on Sustainable Water Resources Management**
12 to 14 September 2008
Frankfurt, Germany
Website: http://waset.org/
Contact name: C. Lewis
Organized by: WASET

**International School of Hydraulics**
23 to 26 September 2008
Krag, Poland
Website: http://sh.igf.edu.pl/
Contact name: Anna Zdunek
Organized by: Institute of Geophysics, Polish Academy of Sciences

**IFAT China 2008 - 3rd International Trade Fair for Water, Sewage, Refuse, Recycling and Natural Energy Sources**
23 to 25 September 2008
Shanghai, China
Website: http://www.ifat-china.com
Contact name: Ms Andrea Graf
Organized by: Munich Trade Fairs International Group