Two-Dimensional Offshore Oil-Spill Model for Eastern/Northern Trinidad and Tobago

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Abstract: There were no two-dimensional offshore oil-spill models found which were specific to the region of Trinidad and Tobago. Analysis of oil-spill reports showed that the use of these models to map the movement of the spills was becoming more prevalent. This paper presents a two-dimensional vector model to determine the movement and position of a theoretical offshore oil-spill occurring off the Eastern Coast of Trinidad. The variables used in the model were wind velocity and current velocity. The final plots obtained would give a generalised mapping of the boundaries of the oil on the ocean’s surface for a given film thickness (assumed constant). The film thickness of the spill was assumed to be constant at all points on the spill map. However, this may create a situation where the plot would be an under-estimate of the actual area affected as the film thickness would vary from the source to the boundary of the spill area. There was also no current data for local oil-spills to compare the plots, which restricted the amount of refinement that could have been done to the model to improve its accuracy. Despite these limitations, the paper would provide a foundation for further development of an offshore oil-spill model for the country.

Keywords: Two-dimensional Vector Model, Oil-Spill Movement

1. Introduction
The Deepwater Horizon blow-out, which occurred in the Gulf Coast of the U.S.A. in 2010, has added fuel to discussions about oil-spills and their impacts, economically and environmentally. Man’s role and responsibility in preventing and mitigating oil-spills have been discussed, clean-up methods assessed and models developed to determine oil spill movement.

The literature review stages of this research involved the analysis of several publications as well as the summarising of reported oil-spills occurring from 2001-2010. These two steps indicated that the development of a generalized model for Trinidad and Tobago would be favorable.

Data for the 2001-2010 oil-spills was obtained from the Centre of Documentation, Research and Experimentation (CEDRE, 2010, 2011). During the period, there were forty-six reported spills, however, only thirty-seven of these were applicable as six were Inland spills and the remaining three did not have sufficient information. The thirty-seven spills were split into two main categories depending upon their source, whether they were from a ship or rig/drilling operations.

The spills from ships were further divided into categories based upon the cause of the spill:
1) Poor weather – Refers to events where strong winds or rough seas caused the vessel to suffer hull damage or take on water and usually involved a single vessel.
2) Collisions – Refers to when a vessel ran aground or two or more vessels collided and it was out of the control of the humans on board.
3) Human error – Refers to situations in which there was some failure to follow protocol or definitive action could have been taken to avoid the spillage.
4) Terrorism – Refers to malicious attacks on vessels by groups or individuals either to capture or sink the vessel.

The three spills originating from rigs were a) Statfjord A, Norway in 2007, b) West Atlas, Australia in 2009 and c) Deepwater Horizon, U.S.A. in 2010. The use of a model to determine the movement of the spilt oil was seen to have occurred in the cases a) and c).

2. Selection of Modelling Approach
Guo and Wang (2009) developed a model for an oil spill in coastal waters and included variables which compensated for factors such as advection, turbulent diffusion and mechanical spreading. They derived a numerical model which took into account the work of Salamon et al. (2006), who proposed the use of Fractional Brownian Motion (fBm). The final numerical model showed favourable two-dimensional results for their data sample (Guo et al., 2009; Guo and Wang, 2009). It was stated that errors could arise due to vertical entrainment of the oil into the water column. The model was primarily
two-dimensional.

Guo et al. (2009) incorporated several other variables such as evaporation, emulsification, shoreline deposition and they also discussed the effect of vertical motion on the spill. This model utilised two programmes “Three-dimensional Free-Surface Hydrodynamics Model (POC)” and “Third Generation Wave Model (SWAN)”, which served as a pre-cursor to the intensive mathematical methods involving Eulerian and Lagrangian techniques. They compensated for the vertical motion by utilising models developed by Tkalich and Chan (2002) and Chao et al. (2001).

The software and advanced mathematical techniques utilised in these papers were not available therefore a more basic approach had to be devised, this lead to the use of a vector approach as the foundation for the model. The entire scenario would be represented by a series of vector fields which would overlap and their final result would be the location and boundary of the oil-spill.

Since vectors were being used, it provided two options to serve as the platform for the model (i.e., MATLAB or MS Excel). MS Excel was chosen as it was considerably easier to develop the basic framework for the model and it was easier to troubleshoot. When the model produced favourable results it would then be set-up in MATLAB as the user-interface would be significantly easier for a new user to input data.

Zhong and You (2011) provided insight into the variables affecting the movement of an oil-spill below:

1) Wind speed and direction
2) Current speed and direction
3) Volumetric flow from the source
4) Wave action
5) Solubility of the oil in water/Emulsification
6) Rate of evaporation of the lighter fractions/Sinking of heavier fractions.

The two-dimensional model developed for Trinidad and Tobago incorporated the first three variables from the list.

3. Analysis of Three Variables

3.1 Wind Speed and Direction

Trinidad and Tobago is affected by the North Eastern Trade Winds, which means that the winds would be heading mainly in a Western to West-South-Western direction and have speeds which average 4.1 ms⁻¹ and may gust to 25.7 ms⁻¹.

3.2 Current Speed and Direction

The main surface current which influences this region is the Guiana Current which flows up along the South American coastline past Suriname, French Guiana and Guyana. It would be heading in a North-Western direction by the time it passes the islands of Trinidad and Tobago. This current has recorded speeds within the range of 0.41 ms⁻¹ to 1.23 ms⁻¹.

3.3 Volumetric Flow-rate of Oil from Well-head

The volumetric flow-rate is assumed to be constant when it is being input into the model, however, with some minor manipulations the flow-rate can be adjusted on a day-by-day basis. A similar approach is taken with regards to the film-thickness of the spill on the surface, this too can be adjusted on a day-by-day basis but it is assumed to be constant for easier demonstration.

4. Development of Model

Each of the variables selected was represented in terms of a vector field. The flow of oil from the source was represented by a radial vector field whose centre was over the well-head. The radius of this vector field would be dependent upon the volumetric flow-rate from the well-head. The wind and currents were represented by uniform vector fields in which the magnitude would equate to the speed and the direction represented by the vector angle.

As previously stated the model was initially developed using MS Excel for easier manipulation of the variables.

4.1 Simulation of Spill Spreading (Radial Source)

A unit circle with sixteen Reference Points on its circumference, each spaced 22.5° apart with 0° being equivalent to “North”, was used to represent the spill. The component vectors i.e. horizontal (i) and vertical (j) components were determined by the use of basic trigonometry and the “Tangent” function (see Table 1).

<table>
<thead>
<tr>
<th>Direction</th>
<th>Bearing (°)</th>
<th>i Component</th>
<th>j Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>0.0 / 360.0</td>
<td>0.000</td>
<td>1.000</td>
</tr>
<tr>
<td>NNE</td>
<td>22.5</td>
<td>0.382</td>
<td>0.923</td>
</tr>
<tr>
<td>NE</td>
<td>45.0</td>
<td>0.707</td>
<td>0.707</td>
</tr>
<tr>
<td>ENE</td>
<td>67.5</td>
<td>0.899</td>
<td>0.437</td>
</tr>
<tr>
<td>E</td>
<td>90.0</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>ESE</td>
<td>112.5</td>
<td>0.899</td>
<td>-0.437</td>
</tr>
<tr>
<td>SE</td>
<td>135.0</td>
<td>0.707</td>
<td>-0.707</td>
</tr>
<tr>
<td>SSE</td>
<td>157.5</td>
<td>0.382</td>
<td>-0.923</td>
</tr>
<tr>
<td>S</td>
<td>180.0</td>
<td>0.000</td>
<td>-1.000</td>
</tr>
<tr>
<td>SSW</td>
<td>202.5</td>
<td>-0.382</td>
<td>-0.923</td>
</tr>
<tr>
<td>SW</td>
<td>225.0</td>
<td>-0.707</td>
<td>-0.707</td>
</tr>
<tr>
<td>WSW</td>
<td>247.5</td>
<td>-0.899</td>
<td>-0.437</td>
</tr>
<tr>
<td>W</td>
<td>270.0</td>
<td>-1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>WNW</td>
<td>292.5</td>
<td>-0.899</td>
<td>0.437</td>
</tr>
<tr>
<td>NW</td>
<td>315.0</td>
<td>-0.707</td>
<td>0.707</td>
</tr>
<tr>
<td>NNW</td>
<td>337.5</td>
<td>-0.382</td>
<td>0.923</td>
</tr>
</tbody>
</table>

The Unit Vector for each Reference Point can be represented as shown below:

\[ \mathbf{S}_R = (x)\mathbf{i} + (y)\mathbf{j} \]  

…Eq.1
Where,
\( S_R \) – Reference point where subscript “R” identifies a specific point \( 1 \leq R \leq 16 \).
\( x, y \) – Magnitude of the horizontal and vertical components at each Reference Point’s Unit Vector.
\( i, j \) – Term denoting “Horizontal” and “Vertical” component vectors respectively.

Each of these Reference Points was then multiplied by a constant term, \( G \), which would have represented the radius of the spill when it reached the surface. This term was dependent upon two factors:

1) The volumetric flow-rate of oil from the well-head and
2) The film-thickness selected/determined for the spill on the surface.

It was assumed that the spill would have a perfect radial spreading upon reaching the surface prior to being affected by the wind and currents. This was represented via the following equation:

\[ S_R = G \left[ (x)i + (y)j \right] \] …Eq.2

As there were now a finite number of points representing the boundary of the spill it was now possible to develop a vector equation to simulate the effect of wind and current on the Reference Points.

4.2 Simulation of Wind Vector Field
The component vectors for a given wind direction was obtained from Table 1. This was input into the basic unit vector equation as shown below:

\[ W = (a)i + (b)j \] ….Eq.3

Where,
\( W \) – Wind Unit Vector field equation.
\( a, b \) – Magnitude of the horizontal and vertical component of the Wind Unit Vector.

The “LOOKUP” function in MS Excel was used to facilitate easier recall of the vector components by referencing them to Table 1 for a given “Bearing INPUT” (wind heading). The unit vector, \( W \), was then multiplied by a scalar \( n \) which would be representative of the wind velocity to produce \( W_1 \):

\[ W_1 = n \left[ (a)i + (b)j \right] \] ….Eq.4

It was necessary to adjust the vector, \( W_1 \), so that the effect of the wind on the surface of the water would be properly scaled. This is because not all the wind’s energy would all be transferred to the water surface. Therefore, the introduction of another scalar \( p \), “Effect Factor” was needed:

\[ W_2 = n \left[ (a)i + (b)j \right] \] ….Eq.5

The basic algorithm representing this entire process is shown below:

WIND VECTOR:
INPUT – Wind Bearing INPUT in Degrees (North being 0°).
OUTPUT – “LOOKUP” Table1.
Print ‘i’ and ‘j’ components a and b.

INPUT – Wind Velocity in Knots, n. (Script would convert to ms⁻¹)
OUTPUT – Print: na and nb.
INPUT – Effect Factor, p. (Should be: p < 1).
OUTPUT – Print: nap and nbp.

4.3 Simulation of Current Vector Field
A similar approach as that used to model the Wind Vector Field was used to model the Current Vector Field. The components for the Current Unit Vector were obtained via a “LOOKUP” function:

\[ C = (c)i + (d)j \] ….Eq.6

Where,
\( C \) – Current Unit Vector field equation.
\( c, d \) – Magnitude of the horizontal and vertical component of the Current Unit Vector.

The unit vector is then multiplied by the terms “\( m \)” and “\( q \)”:

\[ C_1 = m q \left[ (c)i + (d)j \right] \] …Eq.7

Where,
\( m \) – Current velocity.
\( q \) – Effect factor of the current

CURRENT VECTOR:
INPUT – Wind Bearing INPUT in Degrees (North being 0°).
OUTPUT – “LOOKUP” Table.1.
Print ‘i’ and ‘j’ components c and d.
INPUT – Wind Velocity in Knots,m. (Script would convert to ms⁻¹)
OUTPUT – Print: mc and md.
INPUT – Effect Factor, q. (Should be < 1).
OUTPUT – Print: mqc and mqd.

4.4 Combination of the Wind and Current Vector Fields
Both vector fields are uniform and on the same plane, therefore, they can be combined via simple vector addition. This produces a single Resultant Vector Field, \( R \), which would then be imposed on each of the Reference Points from above to produce an overall translation of the oil-spill at discreet time intervals (24 hours). When each discreet interval is combined it would produce the total projected motion and give the estimated spill location.

\[ W_2 = n \left[ (a)i + (b)j \right] \] …Eq. 5
\[ C_1 = m q \left[ (c)i + (d)j \right] \] …Eq. 7
\[ R = (nap + mqc) + j (nbp + mqd) \] …Eq.8

5. Results of Simulations
There was no actual spill data to use as inputs for the model to allow for comparison. Therefore, the simulations that were run were for two theoretical scenarios termed: “Best Case 10m³h⁻¹” and “Worst Case 80m³h⁻¹”. These were basically two oil-spills with a volumetric flow rate from the well head of 10m³h⁻¹ and 80m³h⁻¹, respectively. These values are still considered conservative as the...
The smallest estimated flow-rate from the Deepwater Horizon spill was 300 m$^3$h$^{-1}$.

The film thickness for the scenarios was set to be 0.005 m and was assumed to be constant for the entire duration to allow for easier simulation. This, however, can be adjusted as stated earlier to allow for more accurate plots as it is expected that the film would become thinner as the distance from the source increases as long as no obstruction is in the projected path, i.e. landmasses or reefs. Conditions such as wind velocity and current velocity are as shown in Table 2. They were kept constant for both simulations in-order to allow for comparison of the plots.

The Effect Factors for the wind and current were kept constant for the entire duration of the simulation. These were then adjusted to produce a more favourable result dependent upon the volumetric flow rate of oil from the well-head. This particular aspect was where actual spill data and maps would have been a benefit as it would have allowed for better adjustments to the Effect Factors, as a result it leaves room for further work on the model to improve its accuracy.

The model was run several times. Figures 1 and 2 show the Best Case 10 m$^3$h$^{-1}$ Plots, whereas Figures 3 and 4 shows and the Worst Case 80 m$^3$h$^{-1}$ Plots. The Adjusted Effect Factor Plots are depicted in Figures 5 and 6.

<table>
<thead>
<tr>
<th>Day</th>
<th>Wind Speed</th>
<th>Wind Direction</th>
<th>Current Speed</th>
<th>Current Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>W (270.0)</td>
<td>1.6</td>
<td>NW (315.0)</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>WSW (247.5)</td>
<td>1.0</td>
<td>WNW (292.5)</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>SW (225.0)</td>
<td>0.8</td>
<td>WNW (292.5)</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>W (270.0)</td>
<td>0.9</td>
<td>NW (315.0)</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>WNW (292.5)</td>
<td>1.2</td>
<td>WNW (292.5)</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>WSW (247.5)</td>
<td>0.9</td>
<td>W (270.0)</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>WSW (247.5)</td>
<td>1.3</td>
<td>W (270.0)</td>
</tr>
</tbody>
</table>

Table 2. Wind and current velocities used for each run of the model
6. Discussion

Only the development and results of the final model were presented in this paper. There were, however, some previous terms in the model which were eliminated as the model was tested. These terms were eliminated because they produced plots which were too far away from what should be expected in a real oil-spill. A brief discussion of these failed runs would be presented.

6.1 Failed Model Runs

The initial run of the model would be referred to as Simulation-1. This particular version of the model was producing a plot which was expanding as well as having its point of origin moving, indicating that the spill source was moving. Since the model was supposed to produce results for a fixed source the variables in the model were assessed and adjusted thereby allowing the spill to remain centred over the source. This was done by lowering the Effect Factor for both the wind and the current vectors to a value well below one.

After this was done the model produced a plot which stayed over the source and did not move, it only expanded in size, Simulation-2. Once again this is not what is expected in a situation where there would be winds and currents affecting the position of the spill. The spill boundary should be shifting with the wind and current while still maintaining a portion over the source. Simulation-2 was rejected and the model was again re-examined.

6.2 Model Re-Examination

Simulation-2 had a term referred to as the Growth Factor, $F$, which caused the radius of the oil-spill to increase at a rate determined by the amount of time which had elapsed from the start of the oil-spill. This was eliminated thereby avoiding the results which occurred earlier.

It was then decided to treat the oil-spill as a series of discreet events based upon time. For instance, if a time period of twenty-four hours was selected, the output at the end of DAY-1 would be used as part of the INPUT for the run on DAY-2, the combined OUTPUT from DAY-2 would then be used as part of the INPUT of DAY-3 and so the model would continue. The combined OUTPUT from DAY “$Z$” would be used as the INPUT for DAY “$Z+1$”.

This is why Figures 1, 3 and 5 each have fifteen circles for a 5-Day run, each representing a specific release for a twenty-four hour period. These circles, however, are seen to be overlapping which would imply that they would produce an under-estimate of the actual area of coverage of the oil-spill. Therefore the boundary marked by the model would represent the Minimum Area Affected by the spill. Persons involved in clean-up and combat would now have an idea as to where the oil should move allowing them to set booms or release dispersants accordingly.

6.3 Final Model

The final model was basically an imposition of Equation 8 onto Equation 2 on a day-by-day basis using the respective wind and current parameters. This would be referred to as Simulation-3. The model used a series of discreet intervals as stated above. Basically on DAY-1 the spill would be a simple representation of Equation 8 imposed onto Equation 2. At the end of DAY-2, however, instead of applying Equation 8 only to the circle representing that twenty-four hour period, the Resultant Vector Field was applied to both circles for DAY-1 and DAY-2. This procedure was repeated over the successive days, with the Resultant Vector Field being imposed upon the respective day as well as the previous days.

The final plot was a combination of all the OUTPUTS and the maximum boundary was outlined in an attempt to compensate for the over-lapping of the circles.

When the behaviour of the model in Simulation-3 was considered it was seen that as the days progressed the entire oil-spill area was being shifted in accordance with the Resultant Vector Field, which was considered to be
highly favourable for the model as it was producing OUTPUTS such as that expected for an actual oil-spill. Therefore, it can be stated that the model can be used for future development by refining some of the other parameters or introducing new ones which shall be assessed in the sections below.

It should always be noted that the plots obtained in this paper were completely theoretical as there was no actual oil-spill data to be input into the model to allow for comparison. If, however, real data was available it would have made it easier to modify and adjust the model to produce more accurate results which would have coincided with what was happening. One of the main things that would be adjusted with the model when real data is being input is the Effect Factors for the wind and the current. These would need to be scaled-up or scaled-down accordingly. It is hypothesised that the larger the volumetric flow-rate from the well-head the larger the Effect Factor would have to be for the wind as it is expected that the larger surface area would mean that a larger proportion of the energy of the wind would be transferred to the oil-spill as it would be in contact for a longer period of time. This was put into the model to test the difference in outputs as seen in Figure 5.

7. Recommendations for Further Work
This model was particularly limited by the fact that it only took a small number of variables into account: wind, current and volumetric flow-rate from the well-head. It is therefore suggested that other variables be incorporated into future work as discussed below.

In other models it was seen that wave-motion is a significant factor which would serve to reduce the area of an oil-spill as it causes the oil to begin mixing with the water in the vertical plane, this is also known as vertical entrainment. However, including vertical entrainment would shift the model into a three-dimensional plot rather than a two-dimensional plot. It may be possible to keep the model in two-dimensions by including a variable which would result in a proportional reduction in the oil-spill area but this would require experimental or real data to compare the plots to test the accuracy of the variable.

The volatility of the components in the oil-spill would also affect the length of time for which the oil would persist on the surface of the water. The lighter fractions would evaporate at a rate which would be determined by the temperature of the water and would thereby reduce the area affected by the spill. Evaporation of the components has been seen, in some previous oil-spills, to significantly reduce the amount of oil. This, however, is dependent upon the type of oil spilt so any variable introduced to the model must take this as well as the water temperature into account.

The effect of mass transfer in determining the boundary of the oil-spill should be considered as there would definitely be a concentration gradient set-up, with the higher concentration occurring near the origin and decreasing as one moves away from it. Diffusion in itself would cause the boundary of the spill to become less defined as the different fractions would have varying rates of movement and would require extensive work and data to generate co-relations.

The effect of the wind can also be made more detailed as it can be expected that the film of the oil-spill would be thicker on the windward side of the spill and thinner on the leeward side. A similar effect is expected with regards to the currents.

Using MS Excel to run the model was not viewed as a negative choice as it allowed for much easier manipulation of the model to locate errors and to make modifications to it in order to develop a suitable output. The only drawback is that the interface might be difficult for a first-time user, this can be corrected by adjusting the layout and data input sections to make it easier to locate and understand. This was a situation that MATLAB could have been able to circumvent as the entire model would have been hidden from the user’s view and only prompts would be presented to them to enter the necessary data via the built-in “fprintf” function.

If the model is developed into a three-dimensional one MS Excel would not be the ideal tool to run the simulations as it would become too tedious. MATLAB should be used as it would be able to produce better output plots. Further work should be done to improve the accuracy of the model. This is currently being done by the incorporation of the work to factor-in spreading and evaporation. The Effect Factors are also being investigated with the use of relevant data to attempt to compare and find some correlations. The model could be improved by the inclusion of more variables and more rigorous testing and running of simulations.

7. Conclusion
This paper is concerned with the development of a two-dimensional offshore oil-spill model for Eastern and Northern Trinidad and Tobago. A vector approach was utilised to simulate the movement of the oil on the surface of the water. The model consisted of the variables: wind speed and direction, oceanic current speed and direction and volumetric flow-rate of oil from the well-head. The wind and current were represented by the use of two uniform vector fields which were combined to produce a Resultant Vector Field. The spill from the source was represented by a circle with unit vectors at specific points on the circumference all radiating from the centre. The Resultant Vector Field was imposed on each of the unit vectors to produce a translation in the circle.

The output from a specific day was combined and used as part of the input for the successive day, i.e. output from Day “Z” would be the input for Day “Z+1” and so continuing until the end of the simulations. The data required to run the simulation would be the wind speed
and direction, current speed and direction, volumetric flow-rate, an assumed film thickness of oil on the surface and terms which would scale-down the effect of the wind and current (i.e., the Effect Factors).

The output obtained from the final model produced plots which had characteristics of previous oil-spills; however, the true accuracy cannot be determined as yet due to the lack of actual spill data to compare the model plots. Recommendations for further work would be to expand the model and try to improve its accuracy by including more variables and comparing it to actual data.

References:

Author’s Biographical Notes:
Avin Hardeo has completed his Bachelor’s Degree in Chemical and Process Engineering at The University of the West Indies. He is currently planning the next step in his academic career by selecting a field to pursue a Master’s Degree. This is most likely to be related to the field of Petroleum Engineering. Mr. Hardeo is employed at the Ministry of Energy and Energy Industries of Trinidad and Tobago under the Associate Professional Programme.