CFD modelling and analysis of the trajectory and behaviour of oil pollutant particles in the Ghanaian territorial waters

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ABSTRACT

Petroleum activities like production, transportation and storage have placed Ghanaian waters among zones negatively impacted by human activities. These places are occupied by human occupations and its associated risks. Oil pollution in the environment affects biota and degrades human health. Predictive and descriptive tools have made the assessment of this situation possible for water quality management. In addition, these tools help in contingency planning in dealing with potential threats in the environment. In this research, the MOHID hydrodynamic numerical model was used to render forecast capacity for the possibility of finding susceptible areas to spilled oil particles in the Ghanaian waters from human activities around the region. The concept of nesting domains was used to reduce the cost and processing time (i.e. CPU time, for computation. The hydrodynamics was modelled under three levels and validated with an average deviation of 14.00% and correlation factors above 0.80 from measured results. To locate possible shorelines susceptible to oil particles, random locations and oil exploration sites were used as discharge points for the simulations. In all, about 8 locations were included for the research and they are as follows: (2.9°E, 4.4°N), (1.7°E, 4.6°N), (0.9°E, 4.9°N), (0.9°E, 4.6°N), (0.3°E, 5.2°N), (0.3°E, 4.6°N), (0.5°E, 5.5°N) and (0.5°E, 4.6°N). In conclusion, it took the oil particles 2 days, 6 hours; 1 day, 17 hours; 3 days; 4 days; 1 day; 4 days, 1 hour; and 22 hours for the first seven locations to get beached at the shore. For particles located at (0.5°E, 5.5°N), they were beached outside the Exclusive Economic Zone (EEZ) of Ghana. The study has revealed that the territorial waters of Ghana acts as beaching sites for oil pollutants independent of the discharge location.

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Introduction

Most Ghanaian petroleum resources are discovered on the Gulf of Guinea which also doubles as the stage where most of the petroleum activities like up-stream processes, transportation, temporal storage, etc. occur. These activities can be
classified into natural (i.e. fate of oil in the environment) or man-made (i.e. drilling, storing, etc.) and they both form possible ways that oil particles can enter into the Ghanaian waters [20]. The occurrences of these petroleum activities have placed Ghanaian waters among zones negatively impacted by human activities. These places are occupied by human occupations and its associated risks like polluting the sea. Oil pollution in the environment affects biota and degrades human health. Predictive and descriptive tools have made the assessment of this situation possible for water quality management.

Consumption of petroleum products will keep on rising as the demand for energy increases due to changes in lifestyle and government interventions like increased access to electricity. In the wake of oil incidents, Contingency Plans are used to mitigate the possible effect of oil in the environment and also shows how to recover and dispose off the pollutants safely. To protect the ecosystem, the Plan gives the possible sites, slick area, fate of oil and any situation that may occur during the spill and as the clean-up exercise unfolds. The country as at now lack such a document to help responders and clean-up personnel in that regard.

Risk assessment evaluation is an important stage in contingency planning for estimating the slick area, slick velocity, particles settling time and particles settling sites for operational purposes [3,9,10,22,20]. This information can be obtained using results obtained from either numerical simulation or from satellite information [16,4,21]. Unlike numerical simulation, Satellite information proves to be the best as it gives real time information. Numerical simulation over takes satellite when it becomes necessary to hold interactive training sections for responders without polluting the environment [16].

For the numerical simulations, various modelling tools and approaches have been proposed, [5,18,19]. In the works of [7], they shown the need for proposing appropriate risk assessment for oil spill using numerical tool to address the issue. At the end of their research they mapped out risk index for the study places and came out with five risk areas in the Chinese sea and this has helped in the prevention and readiness needed in planning for ways in combating oil spill.

In 2007, large quantities of oil were discovered in Ghana which has made it part of the Oil Producing Countries [2,20]. This situation mandated the country to find efficient ways of protecting the Ghanaian environment from possible spilled oil from petroleum activities from entering into the environment through contingency planning. The first devastating oil spill in the country is yet to be recorded as the country enjoys both social and economic development.

The country has some shared values like industries, diversified ecosystem, schools, etc. and the need for updating the Contingency plan for Ghana will be welcomed as all these resources are scattered all along the coast. A proper update that will give responders and clean-up personnel alike to have an opportunity to evaluate their scenarios without any physical environmental impact will be the use of numerical models. Numerical model form part of predictive and descriptive tools for water quality management to investigate potential threats in the environment [23,16,20].

Oil undergoes certain changes (i.e. dissolution, evaporation, sedimentation, etc.) when exposed into the marine environment which can be put into two groups. These changes are affected by the conditions in the environment (i.e. salinity, temperature, water current, etc.). The research was to create a model to help study the combine effect of oceanic and atmospheric variables on idealised oil pollutants in the territorial waters of Ghana. Some of the atmospheric variable considered are radiation, atmospheric pressure, wind and wind stress and precipitation. The oceanic parameters are salinity, temperature, mass discharge and density distribution. These idealized particles where given some characteristics (i.e. physical and chemical). In this work the Oil and the Lagrangian modules where used to estimate the settling time, speed of slick and fate of the oil to conclude on the possible sites in the Ghanaian coastal zones that forms the beaching sites for oil pollutants and the possible spatial pattern.

Methods and materials

The approaches considered in this research are elaborated in the following sections.

Implementation of Domain

A 3 Dimensional digital view of the area under study was constructed using data collected from the General Bathymetric Chart of the Ocean (GEBCO) which happens to be a satellite data. Satellite data are not without errors due to resolution and the failure to interpret foreign materials within their view, example floating ships are registered as islands. This situation called for evaluation and editing of the bathymetry data. Data from interesting areas like port and harbour, fishing sites, drilling sites, etc. where forced into the satellite data to improves its resolution to capture small scale activities in the waters. These data cells were filtered and smoothen to improve the depths around neighbouring cells. These events improve the astronomical tide to reflect the field situation.

Hydrodynamic Modelling of Oil Spillage

Figure 1 shows the levels considered to implement the hydrodynamic model. Domains are 3D thermodynamic space under study and the domains found in another domain are called sub-domain or son domain with the former called the parent domain. To reduce the cost and processing time during computation the domains were nested. In that case level 1 in Figure 1 contains the biggest domain followed by the sub-domain in level 2 then the sub-domain in Level 3. This situation allows computing for various physical properties at different levels, e.g. tide in level 1 which is barotropic 2D gridded level followed by salinity, temperature, density, etc. in Levels 2 and 3 which are baroclinic with 43 sigma vertical layers and
3D. During nesting information flows from the parent domain to the sub-domains, (i.e. the boundary conditions for the sub-domains are obtained from the parent domain which happens to be the largest domain).

In this research two kinds of boundaries were considered to allow the domain to interact with their environment through the transfer of energy and mass. To describe the hydrodynamics of the domain effectively and efficiently, the physical properties were compared with field data for validation and calibration.

The oil simulation was implemented by introducing the oil and Lagrangian modules into the MOHID water hydrodynamic model for the simulation of both the trajectory and oil fate. To trace or simulate the trajectory of the oil particles, the dispersion module was also introduced. This module helps in estimating the new locations of the particles by multiplying the resultant velocity with the time step. This new position is then added to the initial position [1,12].

When oil is exposed to the environment they undergo certain processes called the behaviour or the fate of the oil. The trajectory is predicted by coupling the oil module to the hydrodynamic module which contains the current pattern for the field whiles for the weathering process, it is coupled to the atmospheric module and oil weathering module. The consequence of adding the atmospheric and weathering modules is to estimate the behaviour and evolution of the processes. The oil module uses the lagrangian transport module which takes into account the characteristics of the spilled particles.

The area initially covered when oil is spilled into the environment is estimated by using equation 1 [8]:

$$A_{oil} = \frac{\pi A^4}{B^2} \left( \frac{\rho_{wat} - \rho_{oill}}{\rho_{oill}} \right) \frac{gV_{spill}^{5/6}}{\nu_{wat}}$$

(1)

Where:

$A_{oil}$, $\rho_{oill}$, $\rho_{wat}$, $g$, $\nu_{wat}$, $V_{spill}$, represent initial oil slick area, density of oil, density of water, acceleration due to gravity, kinematic viscosity of water, volume of oil, and A and B are 0.57 and 0.725 [8], respectively.

The density is estimated using equation 2.

$$\rho_{emul} = F_{volw} \cdot \rho_{wat} - \rho_{oill} (F_{volw} - 1) (A_{oil} \rho_{emul} + 1) [1 + B(T_{oil} - T_{spill})]$$

(2)
Where $\rho_{oil}$, $\rho_{wat}$, $\rho_{emul}$, represent the density at reference condition for oil, density of water, density of emulsified oil, whereas A and B are constant obtained experimentally. Values recommended for the constants are, $A = 0.0008$ and $B = 1.8 \times 10^{-1}$ [14].

Viscosity of fluids like oil exposed to environmental factors depends on, temperature emulsification and evaporation [14,13,11] and is given by:

$$
\mu = \mu_{oil} \cdot e^{\left[(AF_{\text{mass}}) + \frac{AF_{\text{vol}}}{(1 + BF_{\text{vol}})} + B \left(\frac{1}{T_{\text{spill}}} - \frac{1}{T_{\text{wp}}}\right)\right]}
$$

(3)

Oil undergoes evaporation when exposed in the environment. The rate of oil evaporated by exposure method as presented by [17], is computed using equation 4:

$$
\frac{dF_{\text{evap}}}{dt} = \text{Coef}_{f\text{mass}}A_{\text{slick}} \exp \left( A - \frac{B}{T_{\text{wp}}} \left( T_{\text{wp}} + T_{\text{dcg}}F_{\text{evap}} \right) \right)
$$

(4)

Where,

$A_{\text{slick}}, F_{\text{evap}}, \text{Coef}_{f\text{mass}}, T_{\text{spil}}, T_{\text{wp}}, T_{\text{dcg}}$ and $V_{\text{initial}}$ represent area of slick on water surface, fraction of oil evaporated, constant for mass transfer coefficient of oil, oil spill temperature, boiling point of oil before evaporation, distillation curve gradient and initial volume of oil. The constants (i.e. A and B) depends on the type of oil and can be determined from experiment.

The rate of water entrained in the oil when emulsification occur can be estimated from [11];

$$
\frac{dF_{\text{volwat}}}{dt} = A(1 + W)^2 \left( 1 - \frac{F_{\text{volwat}}}{F_{\text{final}}^{\text{volwat}}} \right)
$$

(5)

where $W$, $F_{\text{volwat}}$, $F_{\text{final}}^{\text{volwat}}$, and $A$, represent flux of matter in and from the surface, fraction of water volume added at the initial stage, fraction of water volume added at the final stage and constant of emulsification, respectively. Values between $1.0 \times 10^{-6}$ to $2.0 \times 10^{-6}$ are recommended [14].

Entrain droplets of oil in water get dispersed and is estimated using [6]. It accounts for the rate of oil dispersed in kilogram over some time and is computed using equation (6).

$$
\frac{dm_{\text{disp}}}{dt} = 0.11m_{\text{allef}}\left(1 + W\right)^2 \left( 1 + 50\mu_{\text{hlick}}^{1/2} \right)
$$

(6)

where $W$, $h_{\text{lick}}$, $m_{\text{allef}}$, $\mu$, and $\sigma$ represent the wind speed at the surface of water, thickness of slick, amount of oil left in the surface in kg, oil dynamic viscosity (cP), and surface tension at oil water interface (dyne.cm$^{-1}$).

Oil sedimented can be calculated using the formular by [15] and is:

$$
\frac{dm_{\text{sed}}}{dt} = A \sqrt{\frac{E}{V_{\text{wat}}}} k_{\text{lick}} c_{\text{drop}} c_{\text{sed}} D_{\text{pen}} A_{\text{slick}}
$$

(7)

where:

$c_{\text{sed}}, E, k_{\text{lick}}, c_{\text{sed}}$ and $D_{\text{pen}}$, represent oil concentration sedimented, dynamic viscosity of water (kg.(m.s)$^{-1}$), dissipated energy when oil get sedimented, oil stickiness parameter(m$^3$.kg$^{-1}$), oil sediment concentration, and oil droplet penetration, penetration of droplets [6], released energy over a period from surface in J.m$^3$.s$^{-1}$, oil sediment concentration (kg.m$^3$) and oil droplet concentration (kg.m$^3$).

Soluble part of oil undergoes dissolution to form homogeneous mixture and is calculated using equation 8:

$$
\frac{dD_{\text{diss}}}{dt} = AF_{\text{surf}} A_{\text{slick}} R_{\text{diss}}
$$

(8)

Where $A_{\text{slick}}, R_{\text{diss}}$ and $F_{\text{surf}}$ represent slick area of oil, dissolution rate and fractional values of area covered by oil.

**Field Measurement**

To describe the effectiveness and efficiency of the hydrodynamic model for the simulation of oil particles, the results from the model simulations were validated with field data. The field data used for this validation are water level and magnitude of current and its direction. The water level was received from tidal gauges installed at harbours and fishing sites (i.e. Figure 2) located within the $3^{rd}$ domain. Other results of the hydrodynamic model that were also considered are salinity, density and temperature profile.

**Discharge Points for Oil Spill Simulations**

The position where the oil were discharged are shown in Figure 3. These locations comprise of exploration sites, the routes of vessel and additional sites that falls within the domain to capture more discharge points.

The oil particles were taken as idealised objects and additional characteristic like floating, sticking were also allocated to them. The simulations were done for some number of days (i.e. 6 days minimum). The origins for the particles are also assumed to be accidental origin with instantaneous emission.
Results and Discussions

Hydrodynamic Results and Validation

The hydrodynamics model provided the resultant dynamics of the physical properties for the temperature and salinity distribution and also the velocity patterns of the domain considered. The hydrodynamic model results are drawn in Figure 4. Figure 4(a) displays the water level for the tidal gauge installed at point A, whiles Figure 4(b) shows the current magnitude and pattern at the water surface. Figure 4(c-d) show the salinity and temperature profiles, respectively for one of the tide gauges’ location.

Figure 4 shows the validation and pictorial view of the margin of deviation of the model data from field data. It was validated for the following physical properties; tide frequency, current pattern and salinity and temperature distribution. The tide frequency gave an average deviation of 14.00% which can be accounted for under various reasons due to human activities from measured data. Activities like installation of tide gauges close to the shore or harbour, docking of ships close to installed instrument, construction/expansion activities close to installed gauges and the use of obsolete instrument form some of the possible ways. On the other hand, error can be generated due to the resolution of the bathymetry for shallow areas.

Also, the model gave a deviations lower than 20.00% than the measured data were recorded for the sea current moving in the same sense for the current as shown in Figure 4(b). Example a model values of 4.2 m/s was found to be 4.0 m/s from the measured data.

The salinity concentration and temperature distribution from the surface downward are displaced in the figure (i.e. Figure 4(c to d)). The Figures shows the profiles of the properties for some particular locations within the domain from the model results. A profile for the same location was not drawn from measured data because of the inability to locate can Algo float at that shallow point.

Both curves are almost straight downwards due to the mixing potential at the shore. The slight curve for temperature profile at water surface is due to the heat flux or the possibility of having hot water from the land mixing with relatively cold sea water.
Oil Spill location

Figure 3. Oil Spill location

Oil Particles Trajectory

The discharge locations for spilled oil in this work are exploration sites and the routes of vessel traffic. In all, about 8 locations were included for the research and they are as follows: (2.9°E, 4.4°N), (1.7°E, 4.6°N), (0.9°E, 4.9°N), (0.9°E, 4.6°N), (0.3°E, 5.2°N), (0.3°E, 4.6°N), (0.5°E, 5.5°N) and (0.5°E, 4.6°N).

Figure 5 demonstrates the movement of the oil pollutants under the influence of atmospheric and hydrodynamic forces when discharged at Point A. The figure also shows the physical changes as the oil particles are dispersed (i.e. changes in slick area, sedimentation, settling time, etc.).

At the end of the simulation it took the oil particles 2 days, 6 hours for point A; 1 day, 17 hours for point B; 3 days for point C; 4 days for point D; 1 day for point E; 4 days, 1 hour for point F; 22 hours for point G to get beached at the shore. For particles located at (0.5°E, 5.5°N) (i.e. Point H), the particles were beached outside the Exclusive Economic Zone (EEZ) of Ghana. The various times taken for the beaching times can be attributed to the fact that, Ghana experiences low tide and also have an average surface current of 4m/s. One notable observation was the direction of the displaced particles which is in the eastward sense which also delay the deposition of the spilled particles at the shore.

Behaviour of Oil in the Environment

Figure 6 shows the changes that the oil particles undergo when released into the environment. Some of the changes are volume of oil evaporated, volume of oil beached, area of oil covered and oil thickness. Ghana is located around the equator with an average sea water temperature of 28 °C which aids in the evaporation of the oil when spilled into the environment as shown in Figure 5(a). When oil spreads it occupies large area as shown in Figure 5(a) which also aids in the evaporation process. This process reduces the amount of spilled particles in the domain. Some of the oil left in the environment get emulsified and converge at the beach.
Figure 4. Hydrodynamic validation (a) Water level for Takoradi (b) hydrodynamic current pattern (c) Profile for salinity (d) Profile for temperature
Figure 4. Continued

(c) Profile for salinity

(d) Profile for temperature
Figure 5. Oil spill scenario for location A
Figure 6. Physical changes of Oil particles under the influence of environmental factors
Conclusion

The behaviour of spilled particles under the influence of atmospheric and hydrodynamics elements was demonstrated in the Ghanaian territorial waters.

The concept of nesting of domain approach was applied in the implementation of the hydrodynamic model to reduce the cost and processing time during computation. Different types of boundaries and boundary conditions were applied to allow the model to interact with its environment.

An overall validation of the hydrodynamic model was carried out analysing the tide levels, salinity profiles, temperature distribution and surface water current and spatial pattern. The tide level was seen to have an average deviation of 14.00% with a maximum sea current deviation of 20.00%. Current pattern was seen to be moving eastward which happens to be the same as the field results.

The oil spill particles were simulated using nine (9) discharge points. From these scenarios held, only eight had their particles reached at shore. Discharge point (0.5°E, 5.5°N) had its particles moving out of the domain.

From the results obtained from the scenarios taken it shows the vulnerability the whole territorial waters of Ghana to oil pollutants.

To protect the shared values (i.e. industries) scattered at the coast of Ghana, oil spill responders and response equipment alike should be scattered evenly along the coast. For cities that are along the coast should have much response equipment concentration for the possibility of handling large oil accidents swiftly.

Due the infinity needs of the country for money to execute projects for social development it can be recommended that response equipment be positions at the capital town of the coastal regions (i.e. Tema, Accra, and Takoradi) and this is justifiable as it take averagely 8 hours to drive across the whole coast with an average speed of 80 km h⁻¹.

CONFLICT OF INTEREST

Please Sir, this letter shows that we the authors of this research work (CFD MODELLING AND ANALYSIS OF THE TRAJECTORY AND BEHAVIOUR OF OIL POLLUTANT PARTICLES IN THE GHANAIAN TERRITORIAL WATERS) declare that we are in support and have no conflict of interest.'

Declaration of Interest: None

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