Oil Spill Modeling to Develop Response Plans for Guyana

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Introduction

The nation of Guyana is located on the North Eastern coastline of South America. It is a nation rich in agricultural, mineral, and forest resources, but until recently, has had no history of oil development. In 2016, significant discoveries of crude oil were identified in offshore waters at several locations in the Stabroek block by Esso Exploration Production Guyana Limited (EEPGL). In light of these new development opportunities, both public and regulatory concerns were raised about the possibility of oil spills affecting sensitive coastal habitats, the artisanal fishing industry of the country, and other important natural and cultural resources. In 2017, EEPGL undertook a comprehensive program of oil spill modeling to understand the risks from offshore spills and initiated an educational program to communicate the science, risks, and proposed spill response strategies to government regulatory authorities and the public in the coastal regions. EEPGL's Commitment was to complete comprehensive oil spill modeling for the initial proposed projects and to complete the educational programs in the coastal regions prior to the production of first oil in early 2020.

Oil Spill Modeling Overview

At the time of the offshore oil discoveries, Guyana had no specific regulations for oil spill modeling to support Oil Spill Response Plans (OSRP). EEPGL Undertook a best available technology approach to the modeling analyses, reporting, and design of offshore oil spill response. The goal of the program was to examine a cross section of possible releases that represent the range of project risks. This ranged from low volume releases that represent valve leaks, to medium volume releases from fuel loading and crude offloading hose breaks, and finally large volume subsea well head releases that represent worst case discharges from the loss of well control. The goal of the modeling was to determine where the oil is going, when the oil will get there, what resources and habitats are at risk, and what can be done to respond.

The modeling analyses utilized a multi phased approach that examined the following:

- Analysis of historic wind data to determine the wind seasons for the region
- Well head analysis to predict the oil plume trap height, oil plume diameter and offset, and oil droplet size distribution
- Statistical analyses of the range of spill scenarios using historic data to determine spill trajectory probability and timing by season
- Deterministic analyses representing either the shortest time to shoreline impact, or if there is no shoreline impact, the largest on-water oil slick footprint
- A response analysis utilizing the deterministic analysis to examine the performance of offshore response strategies

Seasonal Analysis of Winds

A technical report commissioned by ExxonMobil Upstream Research Company (Berek et al. 2015) describes the results from an analysis of the GROW2012 wind time series data and characterizes the prevailing winds offshore Guyana as blowing from the east-northeast during the winter months (December through May) and from the east during the summer (June through November). These were the wind seasons utilized in the modeling analyses.

The spatial extent of the GROW2012 wind data was not large enough to cover the area where oil discharged within the Stabroek block might be transported; thus, wind data from two global models, NOGAPS and NAVGEM, was used as the source of wind speed and direction time series for the oil spill modeling. Data from the two models was needed in order to assemble a time series that covers the same 10-year period as the hydrodynamics (2005-2014) utilized in the modeling analyses.

NOGAPS

Wind data were gathered from the U.S. Navy Operational Global Atmospheric Prediction System (NOGAPS), a state-of-the-art meteorological model. NOGAPS is a robust global model that forms the backbone of the Navy's ensemble prediction system, providing forecasts of up to 10 days for a number of atmospheric parameters. It is additionally used as a research tool for understanding global atmospheric dynamics, air/sea interaction, tropical cyclone prediction, and meso-scale weather patterns, among a wide range of other applications. NOGAPS predicts global atmospheric parameters for 18 vertical levels, including a 10-m height above the water and land surface. Wind fields from the 10-m vertical level were used for the oil spill modeling.

NAVGEM

The Naval Research Lab (NRL) developed and maintains the atmospheric forecast model called the Navy Global Environmental Model (NAVGEM) that replaced the Navy Operational Global Atmospheric Prediction System (NOGAPS) in 2013. NAVGEM version 1.1 completed operational tests in January 2013 and has been the Navy's operational atmospheric forecast system since March 2013, replacing NOGAPS.

A comparison of the GROW2012 and NOGAPS/NAVGEM wind data at the Stabroek block location was performed in order to examine similarities between the data. The comparison shows that at this location the two datasets define a very similar distribution of wind direction with a predominance of east-northeast and easterly winds. Wind speed in the SAT-OCEAN dataset is slightly higher overall than the NOGAPS speed when the wind is from the east-northeast (winter season).

Current Data

The North Brazil Current (NBC) and the Guiana Current dominate ocean circulation off the Guyana coast (Figure 1). The Guiana Current is part of the regional flow between South America, Africa and the Caribbean Sea, extending from the western edge of the NBC to west of the Windward Islands (Lumpkin 2005). After the NBC crosses the equator, part of the current diverges eastward into the Equatorial Undercurrent, while the remainder of the NBC continues northwestward where at certain times of the year it retroflects (turns back on itself) between 4° and 10° North. At the point of retroflection, rings are shed that propagate northwestward along the Guiana Coast (Lumpkin 2005). Observations indicate that around 70% of the total water volume transported into the Caribbean Sea comes from the Guiana Current, which enters the Caribbean primarily between the Windward Islands and between Grenada and South America (Gyory 2014).

The highest surface velocities of the Guiana Current have been found along the edge of the continental shelf, with a mean speed of 41.6 cm/s and an annual range of 30 cm/s (Febres-Ortega and Herrera 1976). Surface drifter observations conducted by Lumpkin (2005) found that the seasonal variation in the Guiana Current correlates with the deviations in strength of the NBC retroflection and western North Equatorial Counter Current (NECC), which fluctuate in response to the annual variation of wind stress curl in the tropics (Lumpkin 2005). Concurrent with the seasonal weakening of the NBC retroflection and reversal of the NECC, the Guiana Current strengthens and reaches its maximum westward speed of 90 +/- 30 cms-1 in late April and drops to its minimum strength in mid-August to September (21 +/- 30 cms-1 westward), and does not strengthen significantly until late February (Lumpkin 2005).

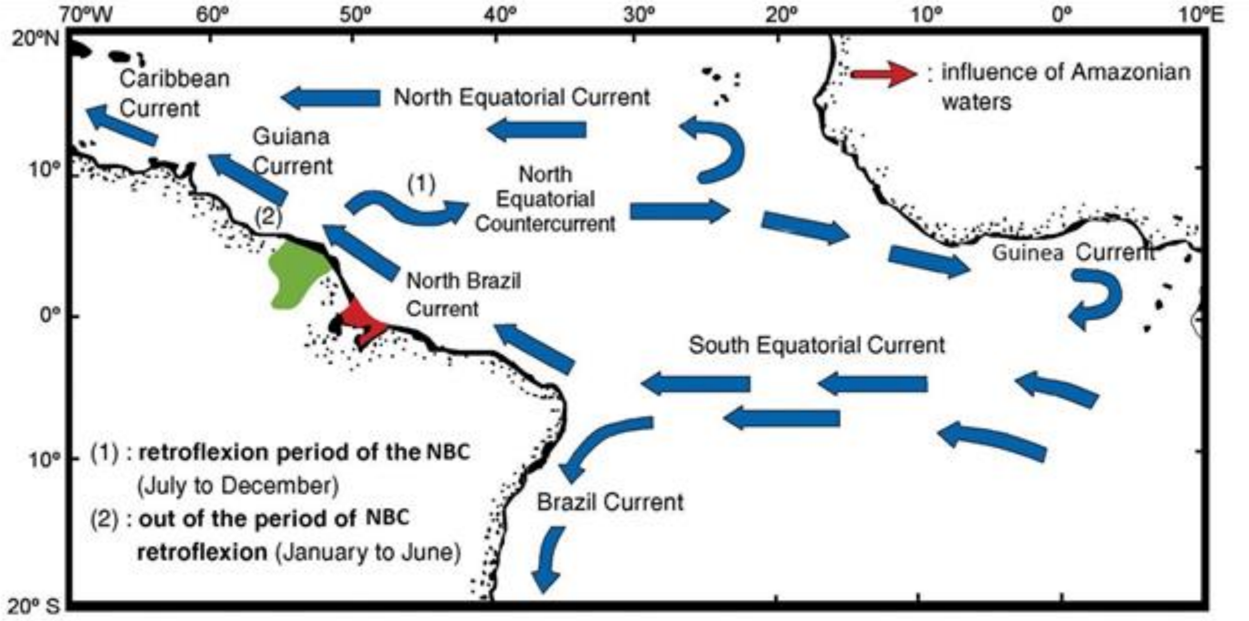


Figure 1. Major ocean surface currents in the Guyana region. Source: Ternon et al. 2002.

The SAT-OCEAN current model is based on the Hybrid Coordinate Ocean Model that includes 3D current speeds in a 4°×4° grid over the Stabroek block region (56°-60°W, 7°-11°N. The horizontal resolution of the model is 1/64°, and the model defines current speed and direction on 64 vertical layers through the water column. The time series data set define 3D currents at a 3-hour interval for the 10 years between 2005 and 2014. The data from the SAT-OCEAN current model were calibrated by current data measured at a location offshore Guyana (8.08°N, 56.95°W) during March to May 2015 (Berek et al. 2015).

Results from initial tests of oil spill model with the SAT-OCEAN current data showed that oil may be transported outside of the model domain depending upon model duration due to strong northwest-directed currents. Current data from the HYCOM global hindcast model (HYCOM n.d.) were appended to the SAT-OCEAN data to extend the coverage to the north and west to encompass the possible range of oil trajectories. The HYCOM Global 1/12° analysis model was selected for this integration because it provides fully 3-dimensional ocean currents for the same 10-year period covered by SAT-OCEAN. The HYCOM currents were interpolated onto a new higher-resolution grid and then vertically interpolated to match the vertical layers of SAT-OCEAN. For the area where the SAT-OCEAN data are available, those currents were used so that the spill model can take advantage of the calibrated, high-resolution currents. Oil is transported by SAT-OCEAN currents while it is within the that model domain. Once oil is outside the SAT-OCEAN domain, it is transported by the HYCOM currents.

Comparison of Current Model with Observations

EEPGL has deployed and maintained a series of deep water current profile moorings and a met station buoy in several prospects in the Stabroek Block, offshore of Guyana. Processed final data sets of the observations were available for first four mooring and buoy deployments spanning March 2016 through September 2017. There were five moorings deployed originally, four of which were instrumented. Two of the current moorings and the met station buoy were deployed in one prospect, and the remaining two current moorings were deployed in another prospect.

The objective of the model to observations comparison was to assess whether the models are capable of capturing the important characteristics of the wind forcing (speed and direction frequency distribution) and the current speeds and circulation patterns (primarily the higher currents associated with the fluctuation of the Guyana current or the passage of NBC rings). It was determined that the measured data are consistent with the synoptic data utilized in the modeling analysis.

Sub-Sea Well Head Modeling

In a well blowout, discharged materials consisting of a mixture of gaseous and liquid hydrocarbons go through three general phases (Figure 2):

1) Momentum jet

The immediate pressure difference between inside the well and the ambient water drives the initial discharge. Due to the relatively high density of deep ocean water, this jet momentum dissipates relatively quickly and is confined to the vicinity of the seabed (on the order of meters).

2) Buoyant density plume

As the discharge moves upward, the density difference between the expanding gas bubbles in the plume and the receiving water results in a buoyant force which drives the plume. As the plume rises, it continues to entrain sea water, reducing the plume's velocity and buoyancy and increasing its radius.

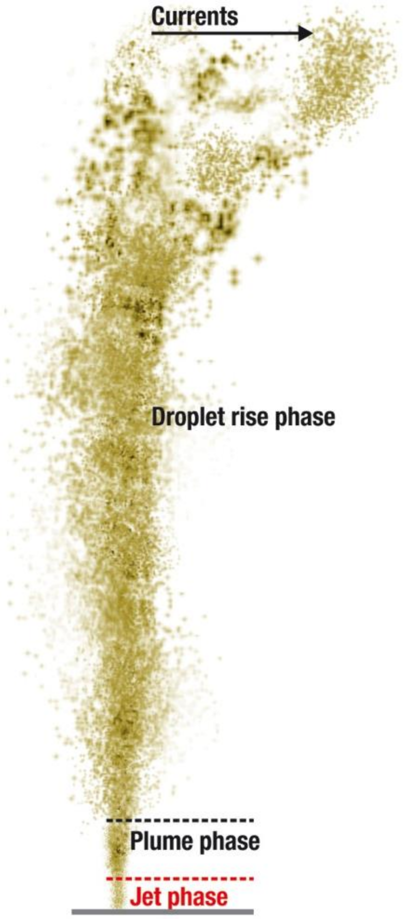


Figure 2. Visualization of a well blowout

The oil in the release is rapidly mixed due to turbulence in the plume, which breaks the oil into small droplets. These droplets (typically a few micrometers to millimeters in diameter) are transported upward by the rising plume; in the near-field their individual rise velocities contribute little to their upward motion.

3) Free rise and advection-diffusion

As the plume reaches the sea surface, its termination, or trap height (when all momentum is lost), it can be deflected in a radial pattern within a horizontal/surface flow zone without appreciable loss of momentum. This radial jet carries the oil particles rapidly away from the center of the plume, while the velocity and oil concentrations in this surface flow zone decrease.

Subsequently, oil particles ascend to the surface solely by their own buoyancy. Rise velocities of oil droplets are much slower than the velocity of a buoyant gas-liquid plume, resulting in particle transport that may take considerably longer to reach the surface and result in transport farther (horizontally) from the release site due to ambient currents.

To simulate this dynamic process, blowout modeling is performed in two steps: 1) a near-field analysis, describing the oil/gas plume generated by the blowout that typically evolves vertically due to vertical processes (relative buoyancy), and 2) a far-field analysis, describing the long-term transport and weathering of the released oil mixture that typically evolves as a horizontal process due to currents and winds.

The near-field model results provide the initial conditions for both the stochastic and deterministic modes of the far-field modeling. In most cases, the near-field results depend more on the blowout conditions (flow rate, gas to oil ratio, and pipe diameter), and less on the environmental conditions (e.g., seasonality). Conversely, the far-field modeling is highly dependent on the environmental conditions such as winds and currents as the main drifting/driving forces.

Near-field Blowout Modeling

The near-field modeling was completed using the OILMAPDeep model. The objective of this first step of the blowout modeling is to characterize the plume mixture (oil, gas, and water) discharged from the wellhead blowout. In most cases, the near-field region occurs only within a few hundred meters of the wellhead.

The blowout model solves equations for the conservation of water mass, momentum, buoyancy, and gas mass using integral plume theory, following work outlined in McDougall (1978).

The results of the near-field model provide a description of the behavior of the blowout plume, its evolution within the water column and the expected initial dilution (concentration decrease) with distance from the wellhead (seafloor). It provides information about the termination ("trap") height of the plume and the oil droplet size distribution associated with the release. These results are used as initial conditions of the far-field fate and trajectory modeling.

Nearfield Model Results (Oil Droplet Sizes)

The oil discharged from the wellhead into the overlying water column is broken into small droplets that are carried upwards in the discharge plume. The plume containing the oil droplets and gas bubbles entrains seawater as it moves upwards, eventually terminating in the water column, or if the water is shallow enough, reaching the sea surface. For the blowout modeled herein, water depth is sufficient to cause the plumes to terminate (trap) within the water column. Once the plume traps, the oil droplets are free to rise through the water column driven by buoyant force until they reach the surface or dissolve. The rise rate of the oil droplets depends on droplet size, with larger droplets rising faster than small. Oil droplets with diameters less than about 70 microns will never surface because the combination of slow rise rate, water depth, and the effects of small-scale turbulence is enough to keep them in the water until they biodegrade.

The OILMAPDEEP model simulates the oil and gas discharge and calculates the oil droplet sizes produced. Droplet sizes cover a range of values which are used as inputs to the SIMAP trajectory and fate model. Figure 3 is a graph of the oil droplet sizes calculated by the blowout model for the scenario modeled at a Stabroek well site assuming a well opening size of 164 in^2 and a discharge rate of 20,000 bpd.

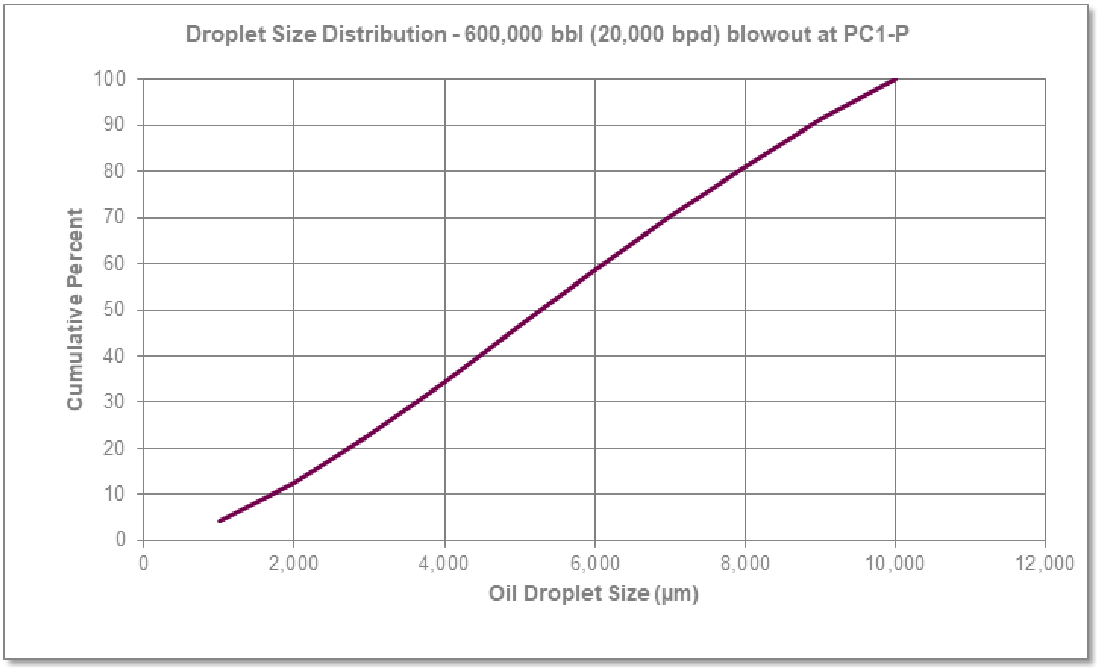


Figure 3. Graphs showing the range of droplet sizes calculated by the OILMAPDeep model for the blowout scenarios at a sub-sea well assuming a discharge of 20,000 bpd.

<u>Far-field and Surface Spill Modeling</u>

SIMAP, was used for all far-field simulations performed in this study. The model quantifies the transport and fate of several components of hydrocarbon mixtures through different compartments of the marine environment over time.

Oil at the water surface is transported by both currents and surface wind drift. Additionally, horizontal and vertical dispersion coefficients in the model reproduce: a) the horizontal spreading of the oil slick due to its natural tendency to thin out (balance of inertial, gravity, and interfacial tensions), and b) the vertical mixing within the upper mixing layer of the ocean. Overall, while those coefficients are important to reproduce the micro-scale processes (emulsion water-in-oil, sediment trapping, minimum thickness), other macro-scale factors play a much bigger role in the overall transport of the oil spill, such as advection due to winds and currents or interaction with the coastline.

Oil spill modeling is performed in two steps: 1) a stochastic analysis that predicts the spatial and temporal probabilistic distribution for a spill event, and 2) a deterministic analysis that identifies the worst-case scenario.

Stochastic Simulations

Stochastic simulations provide insight into the probable behavior of potential oil spills in response to temporally- and spatially-varying meteorological and oceanographic conditions in the study area. The stochastic model computes surface trajectories for an ensemble of hundreds of individual cases for each spill scenario, thus sampling the variability in regional and seasonal wind and current forcing by starting the simulation at different dates within the timeframe of interest. Thus, the stochastic results represent sensitivity to the environmental variability, as each trajectory experiences a different set of wind and current conditions that occur based on the model start date and time.

The stochastic analysis provides two types of information: 1) the footprint of sea surface areas that might be oiled and the associated probability of oil contamination, and 2) the shortest time required for oil to reach any point within the areas predicted to be oiled. Figure 4 displays the statistical probabilities and timing for a 2500 BBL crude release representing a crude oil loading hose break during the summer season. The areas and probabilities of oil contamination are generated by a statistical analysis of all the individual stochastic runs. It is important to note that a single run will encounter only a relatively small portion of this footprint. In addition, the simulations provide shoreline oil contamination data expressed in terms of time for oil to reach shore, and the percentage of simulations in which oil is predicted to reach shore.

Deterministic Simulations

For each spill scenario, one deterministic trajectory/fate simulation is run to investigate a specific “worst-case” spill event that could potentially occur using the same combination of winds and current forcing used in the corresponding stochastic simulation from which it was identified. The worst-case scenario is selected based on the degree of shoreline oil contamination. Different parameters or indicators can be used to compare and assess the degree of shoreline oil contamination, for example “time to reach the coast”, “oil volume to reach the coast”, or “total length of oiled coastline”. Individual spill events simulated in each stochastic scenario were selected based on their rank according to the shortest time to reach shore during each season. A single deterministic spill event ranked as the 95th percentile for the shortest time to reach shore was then selected from each stochastic scenario. These spill events represent meteorological and oceanographic conditions that result in the near minimum time for shoreline oiling to occur. There were five stochastic scenarios in which fewer than five deterministic simulations (5%) were predicted to reach shore. For these scenarios, individual spill events simulated in each stochastic scenario were selected based on their rank according to the maximum surface area oiled. Therefore, a single deterministic spill event ranked as the 95th percentile surface area oiled was selected for these scenarios. Figure 5 displays the corresponding deterministic results from a 95% minimum time to shoreline trajectory from a 2500 BBL crude oil release from a loading hose break during the summer season.

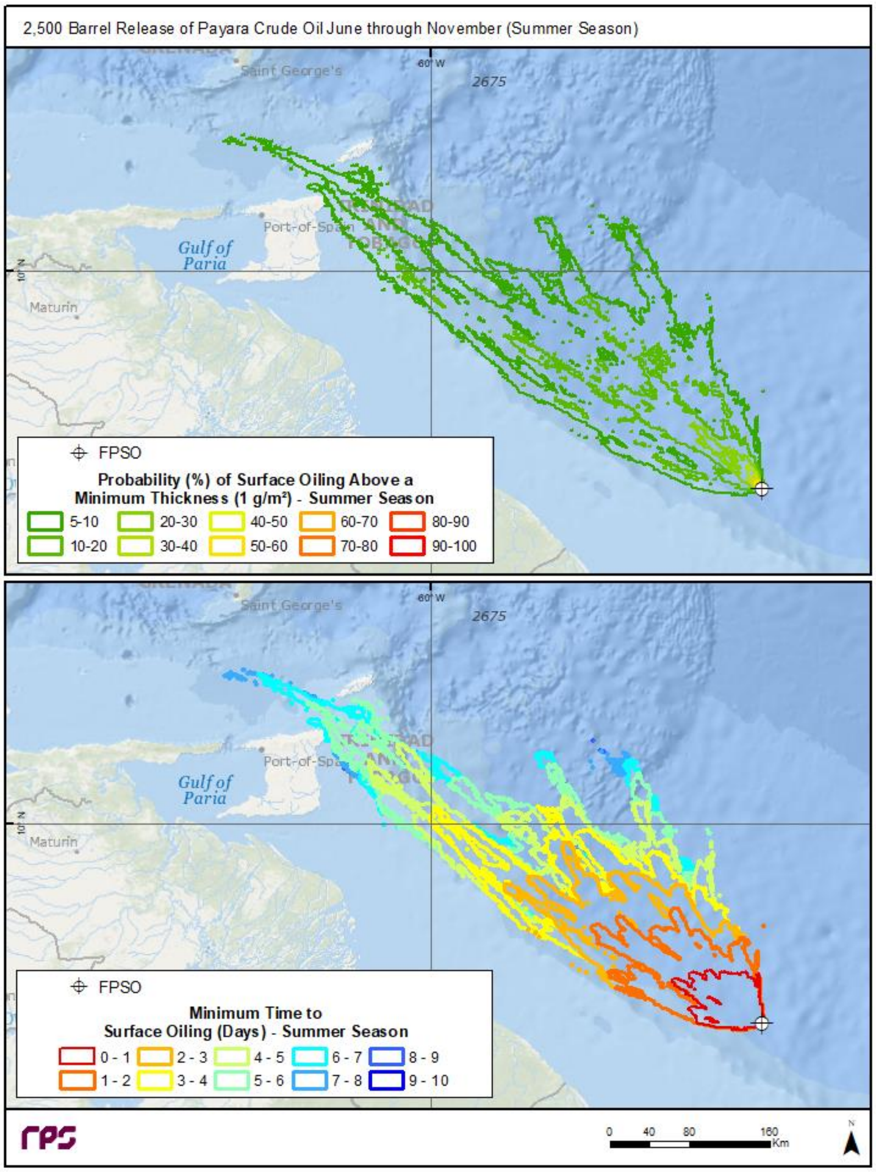


Figure 4. Top panel displays probability of surface oil contamination ≥ 1 during the summer season for a 2,500 bbl instantaneous spill of Payara Crude at the FPSO. Bottom panel displays minimum time for surface oil to exceed 1 µm.

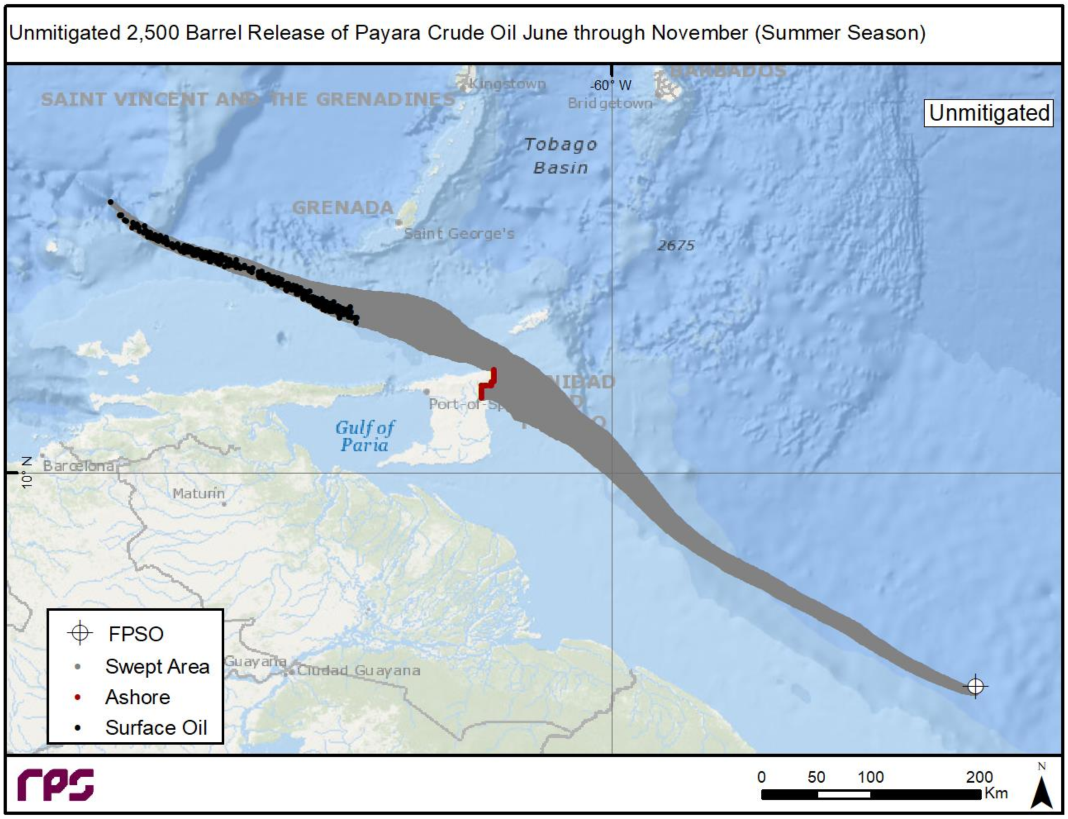


Figure 5. Area swept by surface oil throughout 10-day model simulation for a 95th percentile minimum time to shore scenario for a 2,500 bbl spill of Payara Crude at the FPSO during summer season. Grey area represents surface area wept. Black points represent surface oil remaining at the end of the simulation. Red points represent shoreline oil remaining at the end of the simulation.

Response Modeling

Response (mitigation) modeling was completed for the 2,500 bbl surface release displayed in Figure 6. Response measures included aerial dispersant application, in-situ burning, and mechanical recovery. Summer season average winds range from 5 to 6 m/s (10 to 12 kt) and blow predominantly from the east-northeast. The currents in the area generally flow towards the northwest, parallel to the Guyana coastline. Currents are predicted to transport the surface oil northwest; however, dispersants entrain the surface oil into the water column on Day 2, leaving no oil floating on the water surface. The model-predicted the surface oil trajectory, together with the location of surface and shoreline oil at the end of the 10-day simulation.

Approximately 560 bbl of the spill oil is predicted to evaporate from the surface slick in the first 12 hours, with 586 bbl predicted to evaporate by the end of the 10-day simulation. Surface dispersants (starting on Day 2) are predicted to entrain all of the surface floating oil into the water column. Thus, skimmers and burning are not effective due to a lack of surface oil. No oil is predicted to reach the coast from this scenario.

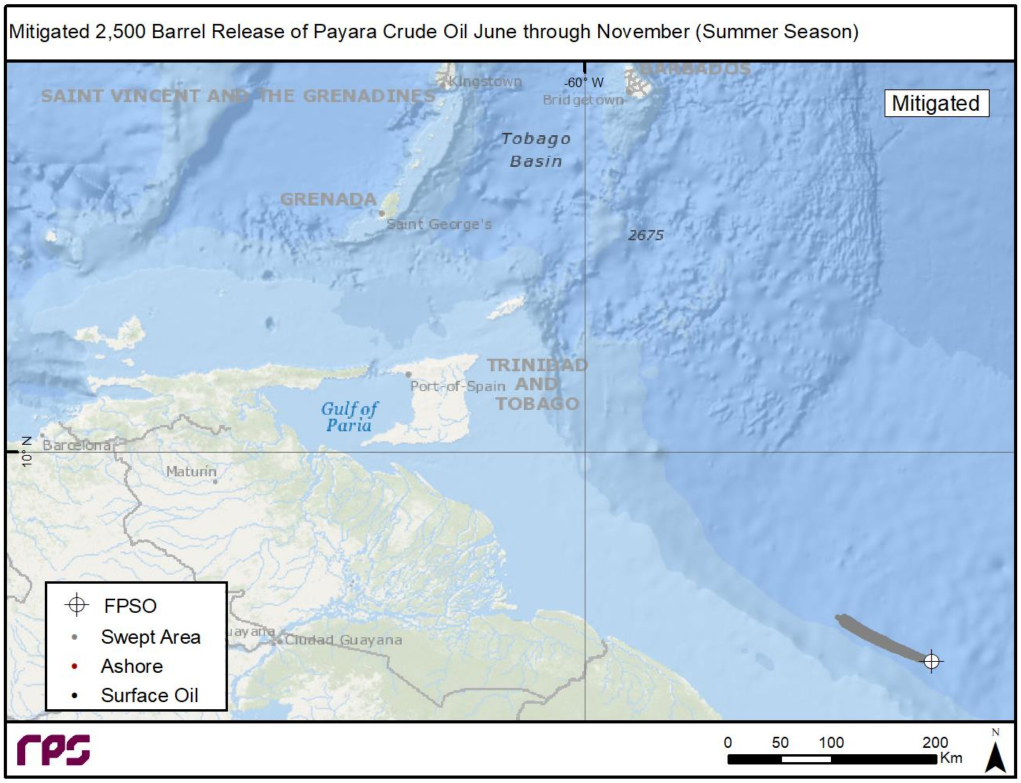

Mitigated 2,500 Barrel Release of Payara Crude Oil June through November (Summer Season)

Figure 6. Area swept results for the mitigated 95th percentile time to shore scenario for the 2,500 bbl release of Payara Crude Oil at the FPSO location during summer season. Grey area represents surface area swept.

A comparison of the fate of the crude oil released in the 2500 BBL crude oil release is displayed in Table 1. This demonstrates that there is sufficient time to mount an offshore response to a spill of this magnitude during the summer to eliminate the surface oil slick and prevent shoreline oil impacts.

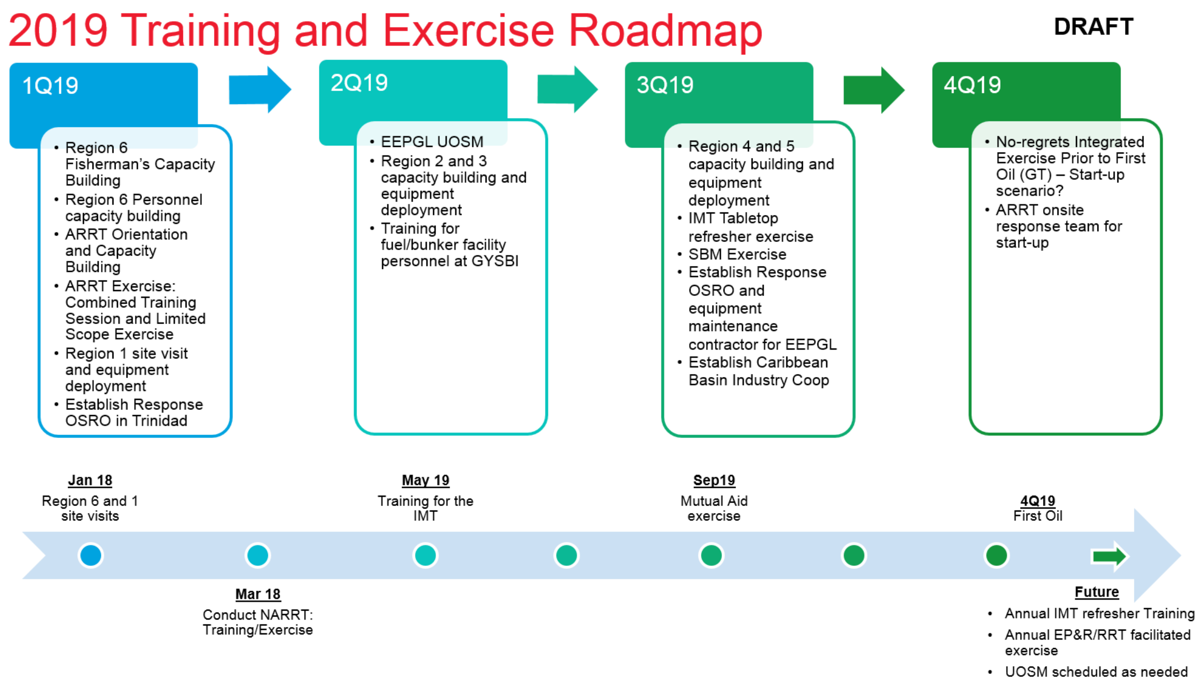
Table 1. Comparison of fates for the unmitigated and mitigated 95th percentile time to shore scenarios for the 2,500 bbl release of crude oil at the FPSO location during summer season

Mitigated FPSO 2,500 bbl Payara Crude Release – Summer Season		
	Unmitigated	**Mitigated**
Shoreline area oiled (km^2)	0.3	0
Oil washed ashore*	401	0
Oil in water column*	4	1,571
Oil dispersed from aircraft *	NA	1,886
Oil burned *	NA	0
Oil mechanically recovered*	NA	0

*Volumes in bbl

Educational Program

The goal of this program was to educate Guyanese Government regulators (EPA, Coast Guard, Civil Defense Commission, Regional Governments and Commissioners, Mayors, etc.) regarding oil spill fate in the environment, the risk of oil spills to Guyanese coastlines and resources, and the strategies for response to offshore oil releases. Additionally, oil spill response equipment from EEPGL in-country inventories were demonstrated and in some cases deployed by trained government representatives. Guyana is comprised of geographic regions, with Regions 1 to 6 representing those along the coastline and being at highest risk from offshore oil spills. It was EEPGL's commitment to complete the training of Guyanese government representatives and meet with members of the public as well as regional government representatives prior to the production of first-oil scheduled in 1Q2020. The 2019 plan for Training and Exercises is presented in Figure 7.



2019 Training and Exercise Roadmap

DRAFT

1Q19
- Region 6 Fisherman's Capacity Building
- Region 6 Personnel capacity building
- ARRT Orientation and Capacity Building
- ARRT Exercise: Combined Training Session and Limited Scope Exercise
- Region 1 site visit and equipment deployment
- Establish Response OSRO in Trinidad

2Q19
- EEPGL UOSM
- Region 2 and 3 capacity building and equipment deployment
- Training for fuel/bunker facility personnel at GYSBI

3Q19
- Region 4 and 5 capacity building and equipment deployment
- IMT Tabletop refresher exercise
- SBM Exercise
- Establish Response OSRO and equipment maintenance contractor for EEPGL
- Establish Caribbean Basin Industry Coop

4Q19
- No-regrets Integrated Exercise Prior to First Oil (GT) – Start-up scenario?
- ARRT onsite response team for start-up

Jan 18
Region 6 and 1 site visits

Mar 18
Conduct NARRT: Training/Exercise

May 19
Training for the IMT

Sep19
Mutual Aid exercise

4Q19
First Oil

Future
- Annual IMT refresher Training
- Annual EP&R/RRT facilitated exercise
- UOSM scheduled as needed

Figure 7. 2019 EEPGL Plan for educational workshops, equipment deployment, and training prior to first oil.

In addition to the workshops, equipment deployment, and training, several spill exercises were held in Georgetown, Guyana. The first involving select EEPLG Subject Matter Experts and the Guyana Government was held in 2018. This was a walk-through of what response planning for an oil spill response would entail. A second much larger exercise was held in 2019. This was a multi-day exercise that included about 60 representatives from the America's Regional response Team and the associated Guyanese government representatives that supported a full Incident Command System based exercise. That exercise demonstrated to the Guyanese Regulatory Authorities the resources EEPGL would bring to bear for an oil spill response should any significant oil spill occur in offshore waters. All EEPGL commitments for training and exercises were met prior to the production of first-oil.

Summary

The discovery of large reserves of crude oil in the offshore waters of Guyana was a unique situation since Guyana had no historic oil production. This discovery raised concerns about oil spills and their effects on coastal resources among both the public and Guyanese regulatory authorities. EEPGL Approached this opportunity by performing a best available technology oil spill modeling analysis using the range of oil spills representing the project's risk. This included both statistical and deterministic oil spill analyses as well as analyses that examined the performance of strategic offshore spill response technologies that would be brought to bear in the event of an accidental release. The modeling analyses were included in a program to educate both the public and Guyanese regulators about oil spill fate, oil spill response technologies and strategies, and oil spill response equipment. This program included several oil spill response exercises that included the Americas Regional Response Team as well as the regulators that would be represented during a response in the event of an actual spill. This program of modeling, planning, and education was completed prior to the production of first-oil in 1Q2020.

References

Febres-Ortega, G. and L.E. Herrera. 1976. Caribbean Sea Circulation and water mass transports near the Lesser Antilles. Boletin del Instituto Oceanografico, 15, 83-96.

Galagan, C. 2017. Results from Oil Spill Trajectory and Fate Modeling to Support a NEBA Offshore Guyana. (Report no. 2017-010, RPS).

Gyory, J., A. J. Mariano, and E. H. Ryan. 2014. The Guiana Current. Ocean Surface Currents. http://oceancurrents.rsmas.miami.edu/atlantic/guiana.html.

Hogan, T.F., Liu, M., Ridout, J.A., Peng, M.S., Whitcomb, T.R., Ruston, B.C., Reynolds, C.A., Eckermann, S.D., Moskaitis, J.R., Baker, N.L. and McCORMACK, J.P., 2014. The navy global environmental model. Oceanography, 27(3), pp.116-125.

HYCOM. (n.d.). HYbrid Coordinate Ocean Model. Retrieved May 2012, from HYCOM Overview: http://hycom.org/hycom/overview

Lumpkin, R. and Garzoli, S.L. 2005. Near-surface circulation in the tropical Atlantic Ocean. Deep Sea Research Part I: Oceanographic Research Papers, 52(3), pp. 495-518.

Jones RK. 1997. A simplified pseudo-component of oil evaporation model. In: Proceedings of the 20th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, 3–5 June. 1997. Vancouver, British Columbia. Emergencies Science Division, Environment Canada, Ottawa, ON, Canada. p. 43–61.

McDougall TJ. 1978. Bubble plumes in stratified environments. J. Fluid Mech. 85(4):655-672.

Rowe, J., Ducharme, J., Frediani., M., McStay, L., Mendelsohn, D., TajalliBakhsh, T., 2018. Results from Oil Spill Trajectory and Fate Modeling – Phase II Offshore Guyana (Report no. 2018-022095, RPS).

Ternon, J.F., J.P. Lefebvre and D. Guiral. 2002. The influence of the Amazonian waters over the French Guiana continental shelf: the CHICO program. VI Workshop ECOLAB, 23-29 September 2002, Belém _PA, Brazil.