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Review

An Overview of Oil Spill Modeling and Simulation for Surface and Subsurface Applications †

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Abstract

In this review paper, we briefly discuss the occurrence of oil spills and their behavior under natural sea conditions and clean-up methods, as well as their environmental and economic impacts. We discuss methodologies for oil spill modeling used to predict the fate of a spill under dynamic physical and chemical processes. Weathering processes such as evaporation, emulsification, spreading, dissolution, dispersion, biodegradation, and sedimentation are considered within easy-to-use modeling frameworks. We present simple models based on the principles of thermodynamics, mass transfer, and kinetics that under certain conditions can predict oil thickness, volume, area, composition, and the distribution of toxic compounds in water and air over time for various types of oil and their products. Modeling approaches for underwater oil jets, including applications related to the 2010 BP oil spill in the Gulf of Mexico, are reviewed. The influence of sea surface velocity and wind speed on oil spill mapping, spill location, oil spill trajectory over time, areas affected by light, medium, and heavy oil, and comparisons between satellite images and model predictions are demonstrated. Finally, we introduce several recently published articles on more recent oil spill incidents and the application of predictive models in different regions. We also discuss the challenges, advantages, and disadvantages of various models and offer recommendations at the end of the paper.

Keywords: oil spill; behavior; weathering processes; simulation; toxicity; prediction; simple models; advanced models; Gulf of Mexico; Persian Gulf

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1. Introduction

1.1. Occurrence

An oil spill is generally defined as the accidental release of oil into seawater from a tanker, offshore production facility, or subsea pipeline. The released substance is typically crude oil, liquid petroleum products, liquefied natural gas (LNG), liquid petrochemicals, or biofuels. The export and import of oil and its derivatives by sea account for nearly 30% of global seaborne trade. Another major source of oil spill incidents is offshore oil production, which contributes approximately 28% of global oil output. According to the U.S. Department of Energy, total world liquid fuel production is projected to reach approximately 105 million barrels per day by 2026 [1].

Oil spills may result from tanker collisions, armed conflicts, attacks on oil platforms, or operational failures in offshore production due to equipment malfunction or insufficient safety measures. The largest recorded oil spill occurred in 1991 during the Gulf War in

the Persian Gulf, where an estimated 5 to 8 million barrels of oil were released into the sea. Another major incident occurred during offshore production in the Gulf of Mexico in April 2010 commonly referred to as the BP, GOM, or Deepwater Horizon oil spill. Between 3 and 5 million barrels of oil were discharged over a span of nearly three months, affecting an area exceeding 100,000 km^2. The total economic cost of the spill was approximately USD 60 billion, and the incident resulted in the loss of 11 lives, according to the National Commission on the BP Deepwater Horizon Oil Spill Report [2]. The initial discharge rate of 1000–5000 barrels per day (bbl/d) eventually increased to approximately 57,000 bbl/d after two months.

The primary objective of this paper is to review existing oil spill modeling approaches applicable to both subsurface and surface water under varying environmental conditions and various types of oil and to provide recommendations regarding their applicability, limitations, and potential for future development.

1.2. Behavior and Treatment

Efforts to clean up oil from the sea usually begin immediately following an oil spill accident. Cleanup methods are complex and challenging and may include physical/mechanical, chemical, and biological techniques. Physical methods include gravity separation, while chemical methods involve the use of substances such as demulsifiers and biosurfactants, as well as in situ burning and flocculation.

The natural behavior of an oil spill is presented in Figure 1. Natural processes play an important role in determining the fate of an oil spill; however, most of these processes are generally slow and time-consuming, with the exception of evaporation and spreading. These natural processes include evaporation, spreading, oxidation, emulsification, dissolution, biodegradation, dispersion, and sedimentation, as shown in Figure 1. The relative rates and contributions of each process to the disappearance of oil are presented in Figure 2 [3–5]. A brief description of each process is provided in Table 1.

Table 1. Brief description of natural weathering processes.

Evaporation
The lighter components of oil may vaporize as heat is absorbed from the sun. Heavier components can also vaporize if the temperature increases. The extent of vaporization depends on factors such as temperature, oil composition and its properties, surface area of the slick, and wind speed. Oil volatility is related to its vapor pressure, and highly volatile oils or petroleum products may vaporize completely and rapidly. For typical crude oils, evaporation can range from 20% to 60%.
Spreading
Oil released on the water surface begins to spread, driven by water currents and waves, which break the slick into smaller particles. Spreading oil reflects light in different directions, creating grey or rainbow sheens. The most critical factor in spreading is the interfacial tension between oil and water—oils with lower surface tension spread more quickly than heavier oils. Other influencing factors include temperature, the volume of oil, and water current. Spreading increases the surface area of the oil slick, thereby enhancing the rates of both evaporation and dissolution.
Dispersion
Dispersion occurs when oil breaks into smaller particles that sink below the water surface. Some of these particles may later rise back to the surface, forming a thin layer of oil sheen, typically less than 0.003 mm thick.

Table 1. *Cont.*

Dissolution
Dissolution is a physical process in which some oil components dissolve into the water, depending on the oil's composition, water temperature, and sea conditions. The most important factor determining the extent of dissolution is oil solubility, which is influenced by temperature, salinity, and the composition of the oil. Although the amount of oil dissolved in water is small compared to the rate of evaporation, it is important from toxicological points of view, especially the dissolved aromatic components.
Emulsification and Oxidation
Emulsification refers to the mixing of oil and water, usually caused by wave action. This process can increase the apparent volume of the oil by up to four times and causes the oil to persist on the water surface for an extended period. Oxidation occurs when oil components react with oxygen in the air, also contributing to the prolonged presence of oil on the sea surface.
Sedimentation
Oil particles on the sea surface vary in size and mass. Heavier particles may sink to the seabed, a process known as sedimentation. This process can be enhanced by the use of chemical dispersants.
Biodegradation
Biodegradation is the breakdown of oil particles in the aquatic environment by microorganisms such as bacteria and algae. This is a slow process that depends on factors such as temperature, oxygen levels, the presence of microorganisms, and the size of the oil particles. Biodegradation primarily affects smaller particles that may remain in the water for long periods.

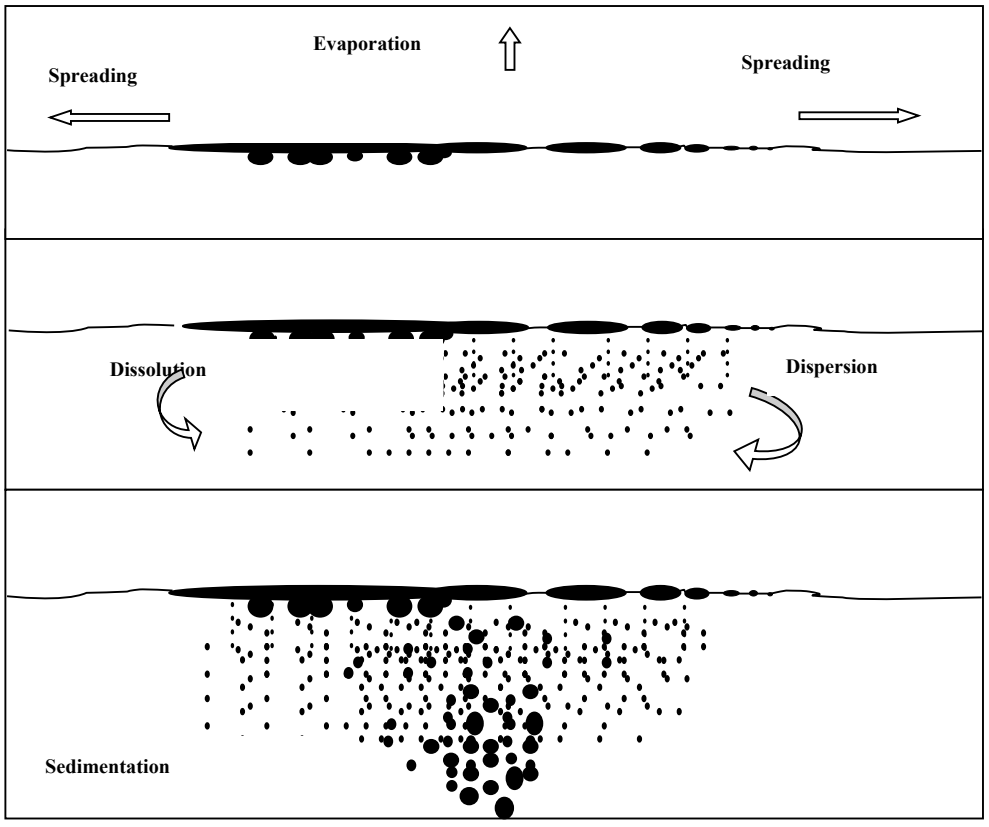

Figure 1. Behavior of oil spill on sea water surface [3].

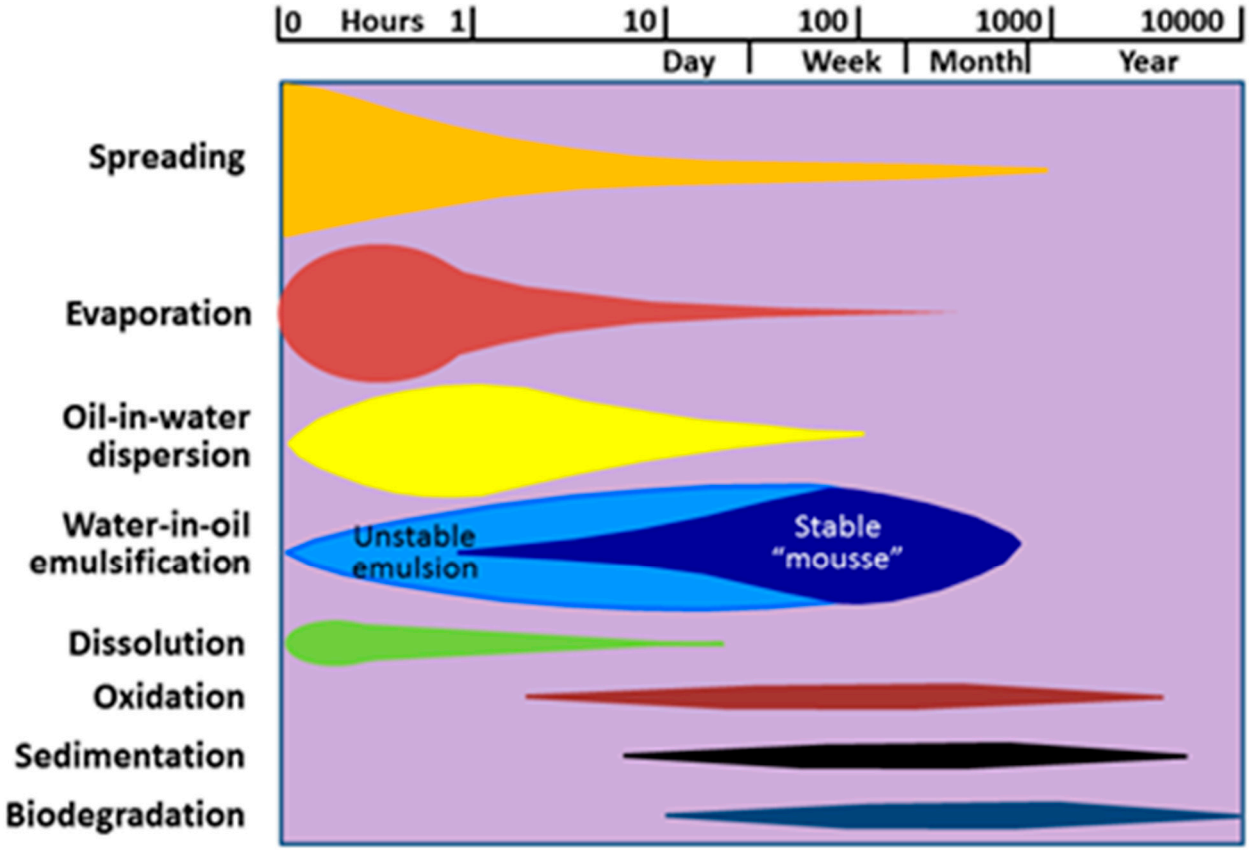

Figure 2. Spreading and evaporation are important in the early hours of a typical oil spill. (Courtesy of SINTEF) [4].

Evaporation is the fastest natural process; however, its rate and extent depend greatly on weather conditions and the type of oil. Gasoline evaporates much more quickly than crude oil or heavy bunker oil. The most important property determining the evaporation rate is vapor pressure. Higher wind speeds and temperatures increase the amount of evaporation. The rate of spreading decreases after a few hours due to the effects of currents and waves. Oxidation, sedimentation, and biodegradation are the slowest processes, as demonstrated in Figure 2.

Use of protective booms is an effective way of preventing oil spreading over water surface and to increase its thickness to facilitate recovery. Dispersants (a kind of surfactant such as fatty acid esters) can be used to slow down the movement of oil slicks to the coastal areas and wetlands, but they cannot remove the oil. Surfactants are released by airplanes or boats with the use of solvents (usually glycol or light petroleum distillates), which help to deliver surfactants at the water–oil interface.

Skimming and mechanical methods to remove oil are effective when the oil thickness is between 1 and 10 mm and sea conditions are calm, with waves less than 1 m. In the case of the Gulf of Mexico (GOM) oil spill, about 1.9 million gallons of oil were released into the water, covering an area of 70,000 square miles and polluting approximately 1100 miles of shoreline [6]. Other estimates put the amount of oil leaked at 4.4 million barrels, with a leakage rate of 56,000 barrels per day [7]. The treatment methods used to contain this oil spill were based on physical and chemical techniques, as shown in Figure 3 for the GOM oil spill [8]. Further discussion on oil spill control was reviewed in our earlier publication [9].

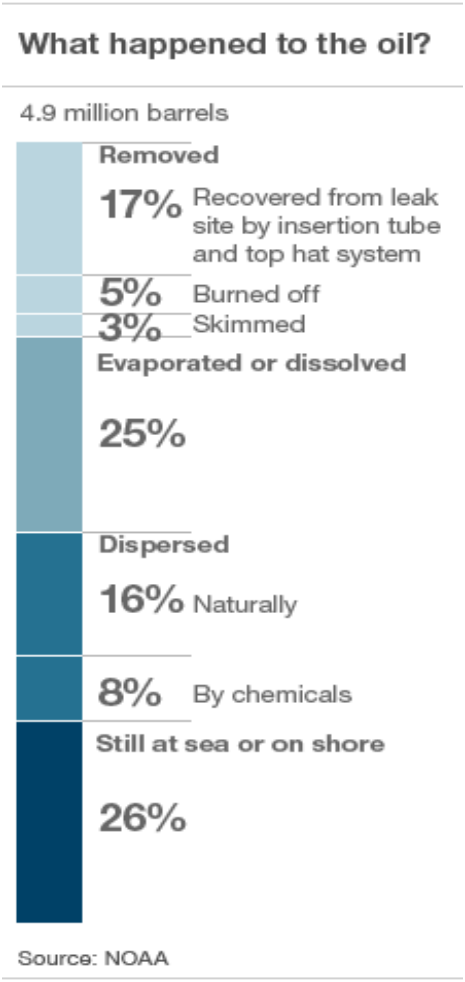

Figure 3. Distribution of BP/GOM oil spill (Source: NOAA).

1.3. Modeling and Simulation

Oil spills can be monitored using GIS or detected by Synthetic Aperture Radar (SAR), an active sensor that captures microwaves from target objects. SAR enables detection of oil spills in sea areas both day and night and under most weather conditions [10,11]. SAR image classification can distinguish between three pollution levels in an oil spill: the central spill area, the surrounding high-pollution zone, and the outer low-pollution layers [12].

The fate of an oil spill depends on the type and composition of the oil, as well as weather conditions. Light oils tend to be more toxic than heavier oils; however, heavy oils persist longer after a spill. An ideal model for predicting the fate of an oil spill should mathematically simulate all dynamic processes shown in Figure 1 over time. Current state-of-the-art models include some, but not all, of these processes in a single framework. Field experiments designed to test these models typically focus on one specific process, as studied and reviewed by several researchers [13–17]. Heavy compounds and residues tend to disperse or sink to the sea bottom [3,5].

Riazi and Alenzi (1999) proposed mathematical relationships for the rates of oil evaporation and dissolution by introducing two temperature-dependent mass transfer coefficients—one for evaporation and one for dissolution—accounting for variable slick thickness [18]. They also provided experimental data on the disappearance rates of various petroleum products and crude oil floating on water under different conditions. Later, Riazi (2016) extended the model to address the continuous flow of oil into the sea [5].

Simulation of the oil jet from a damaged platform or ship is challenging due to the multiple physical processes and forces involved in the evolution of bubble size along

the jet trajectory, both with and without the application of chemical dispersants. Several simulators have been developed for this purpose and are reviewed in the next section. NOAA's prediction of the BP oil spill on May 7 is shown in Figure 4 [8].



Figure 4. Location of protective booms and forecast on May 7 (NOAA, 2010).

2. Modeling Approaches and Results

Generally, models developed and presented in the literature for simulating oil spill behavior can be grouped into two types. The first type consists of simple models that primarily predict rates of evaporation, dissolution, and sedimentation. These models apply to spills without any sea currents and assume no movement. They can predict oil slick volume and thickness over time but do not track the trajectory of the spill. The second group comprises more advanced simulators that include all the dynamic processes shown in Figure 2. These simulators also display the spill's map and movement, as shown in Figure 4.

2.1. Simple Models

The principle of these simple models is based on the assumption that the oil spill remains stationary, and the rate of biodegradation is ignored while the rate of dissolution is considered due to the toxicological importance of hydrocarbons dissolved in water, as discussed by Riazi and colleagues [5,19]. The oil spill is modeled by breaking it down into several pseudo-components, as shown in Figure 5. By applying appropriate thermodynamic and mass balance equations, the amounts of oil evaporated, dissolved, or sedimented can be estimated over time. Figure 6 shows the model's prediction for the rate of dissolution of various components in the sea. Generally, salt concentration reduces the amount of dissolution, while an increase in temperature increases dissolution. Monoaromatics such as benzene and toluene are the most toxic components in the oil, and the model predicts their concentrations in water over time. The characterization methods proposed by Riazi are used in this model to describe the properties of petroleum mixtures [20,21]. These models were extended to oil spills caused by continuous oil flow, such as in the Deepwater Horizon accident [3,5]. The simple model predicted that 25% of the oil remained after 87 days, which closely matches the data shown in Figure 3. Researchers at SINTEF in Norway also developed an "Oil Weathering Model" (OWM), which includes evaporation, dispersion, and spreading processes under Arctic conditions. The model runs on Microsoft Windows, features a user interface, and has its own oil type database, but its applications are limited [22].

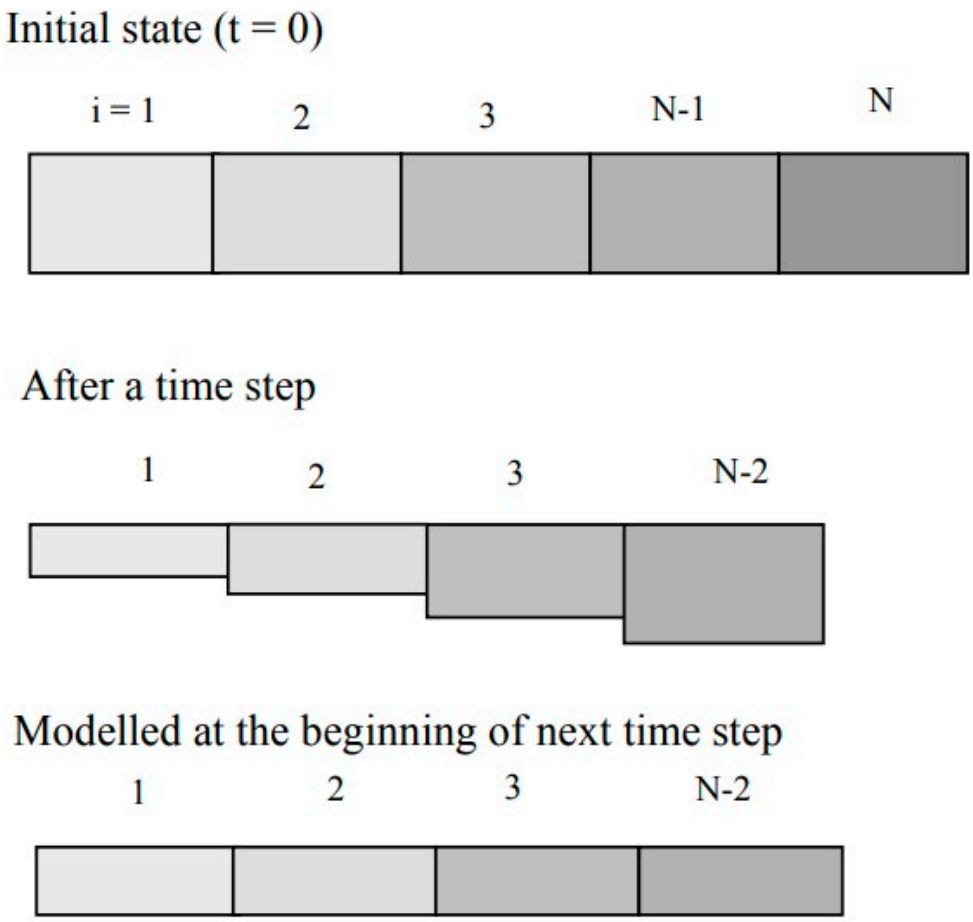

Figure 5. Modelling scheme for an oil spill [18].

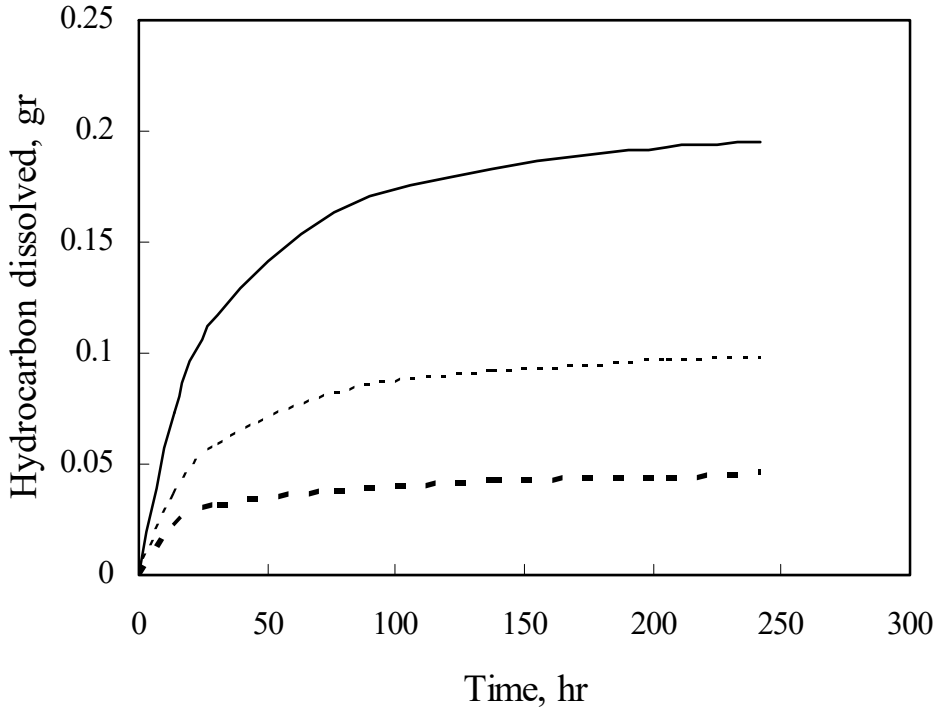

Figure 6. Model prediction for the rate of crude oil dissolution at 20 °C. Total compounds (——), total aromatics (--------), monoaromatics (- - - -) [3].

2.2. Advanced Models

Advanced models simulate oil spills both near subsea fields and in far-field scenarios, including oil trajectory and movement. Three-dimensional oil spill modeling is used to represent oil plumes originating from the seafloor, such as when a blowout preventer fails to stop a sudden gas shock wave, as occurred during the BP oil spill. A major difference between oil plumes from the seafloor and crude oil from the surface is the type of oil involved. Seafloor oil is reservoir fluid that contains light hydrocarbon gases.

Figure 7 shows a turbulent oil jet [23]. The core of the modeling approach is estimating droplet size distribution, where the oil volume breaks into smaller droplets. An example of plume simulation using OSCAR DeepBlow is presented in Figure 8 [24]. These models track the plume as a multiphase volume, including droplets, bubbles, dissolved compounds, entrained seawater, and gas hydrates. On the left, the color scale indicates concentrations of dissolved compounds, while on the right, it shows the plume's height.

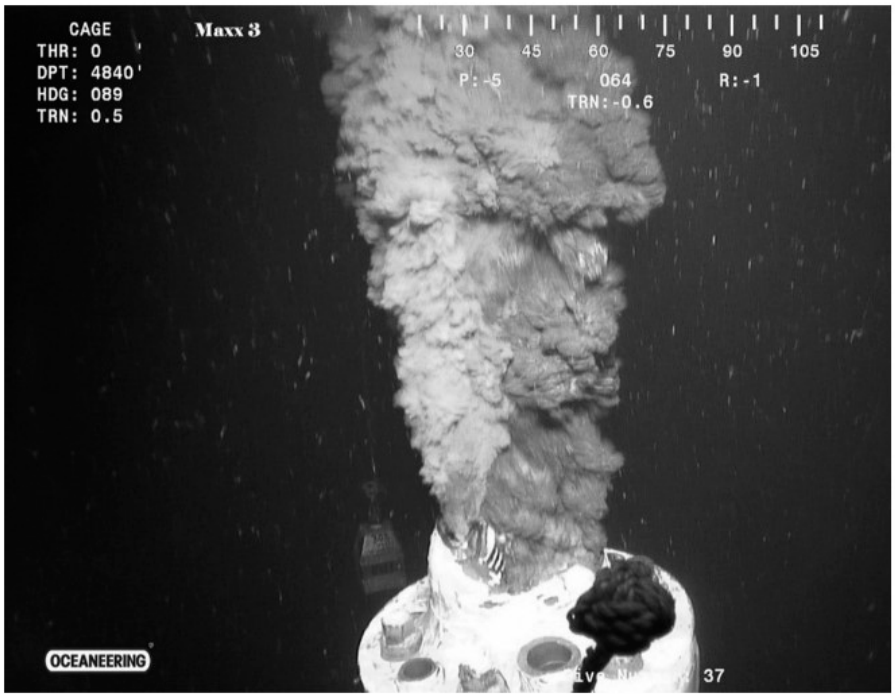

Figure 7. Oil is flowing from damaged well in GOM (www.whoi.edu).

Figure 9 shows the significant effect of droplet size on the amount of oil entrained in water [24,25]. Smaller droplets and lighter oil result in higher entrainment. The effects of biodegradation on oil droplets are shown in Figure 10, where the left image displays droplet distribution without biodegradation, and the right image shows it with biodegradation.

Droplet size is arguably the most important and critical factor in modeling both subsea jet oil and surface oil spills. Detailed modeling approaches for subsea oil plumes are provided by Kotzakoulaki and colleagues in Chapter 8 of *Oil Spill Occurrence, Simulation, and Behavior* [24].

Most advanced oil spill models account for the effects of various response strategies used to manage the spill. These methods include chemical dispersants, mechanical recovery, containment barriers, and in situ burning. Chemical dispersants work by reducing the interfacial tension between oil and water and lowering the oil's viscosity, allowing the oil to break into smaller droplets that can more easily disperse into the water column.

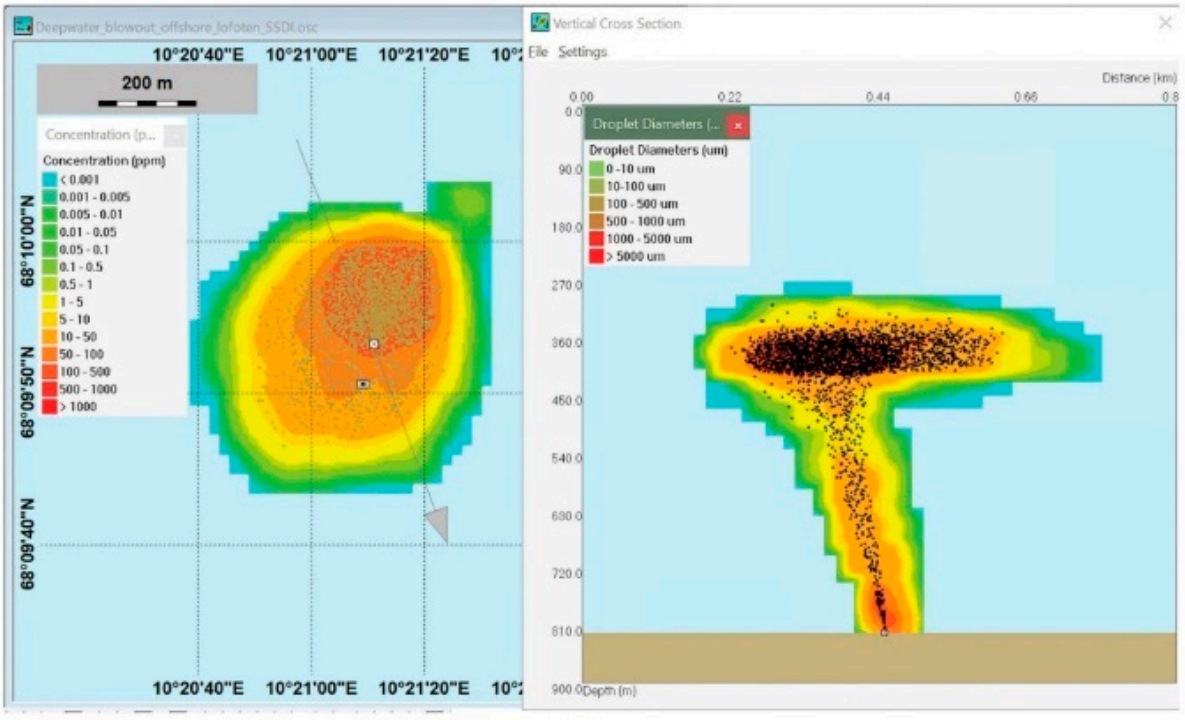

Figure 8. Example of oil plume simulation (Kotzakoulakis, 2021) [24].

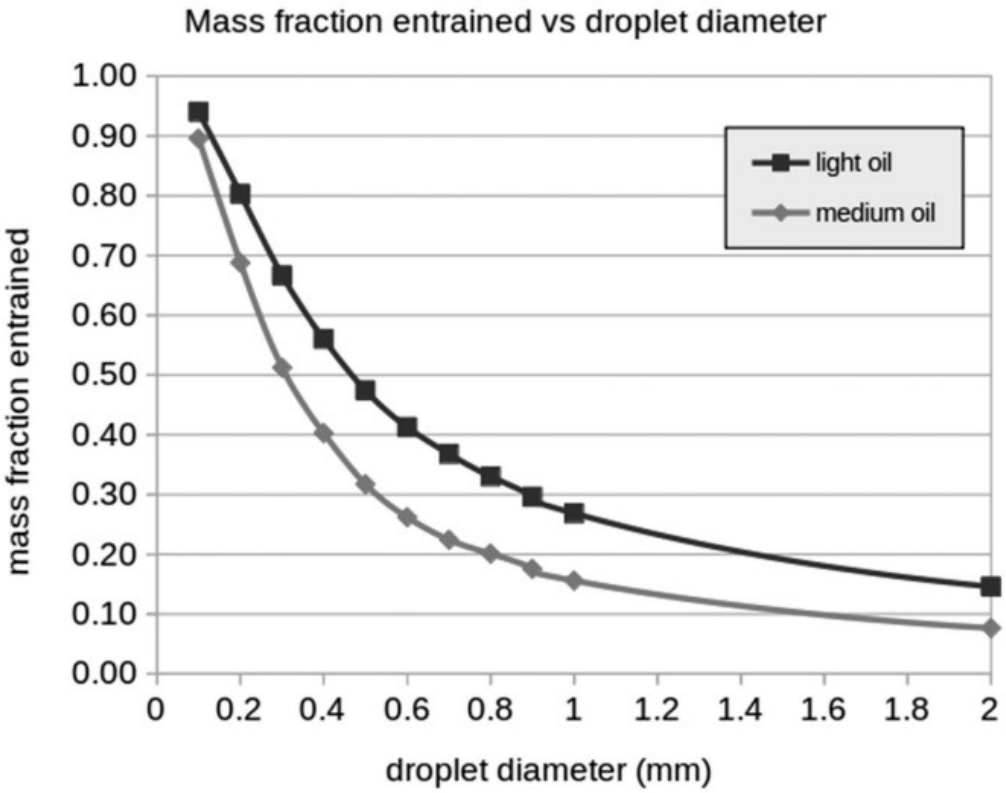

Figure 9. Impacts of droplet size and type of the oil on the amount of entrainment in water (Kotzakoulaki and George 2021) [24].

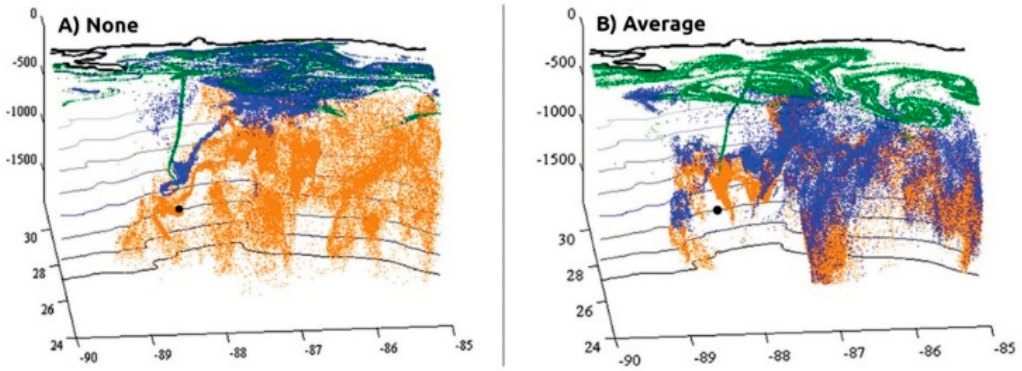

Figure 10. Effect of biodegradation on the buoyancy of oil droplets [26].

One freely available model is the Texas A&M Oilspill Calculator (TAMOC), developed by a research group at Texas A&M University to predict the fate and transport of oil and gas released during subsea accidents. The model is coded in Python and Fortran. Figure 11 shows TAMOC's prediction for the Deepwater Horizon subsea blowout, both with and without the application of dispersants [26]. Further details of this model are provided by Kotzakoulaki and colleagues [24].

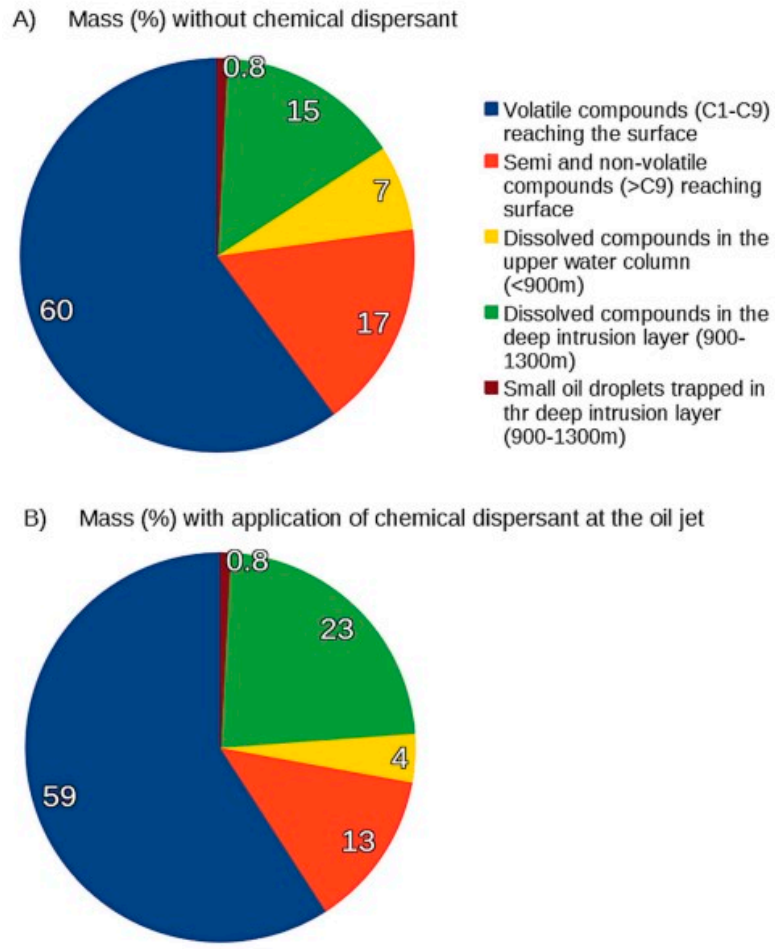

Figure 11. Prediction of mass distribution with and without dispersants from TAMOC Model [3,27].

Figure 12 shows the trajectories of oil movement in the Gulf of Mexico from April through August 2010, based on aerial observations and simulated by NOAA. As shown, the heavier and thicker oil is concentrated at the center of the slick. Another NOAA simulation from May 2010 over a month after the accident is presented in Figure 13. Later, Barker

et al. (2020) reported advancements in the operational modeling of the Gulf of Mexico oil spill [28].

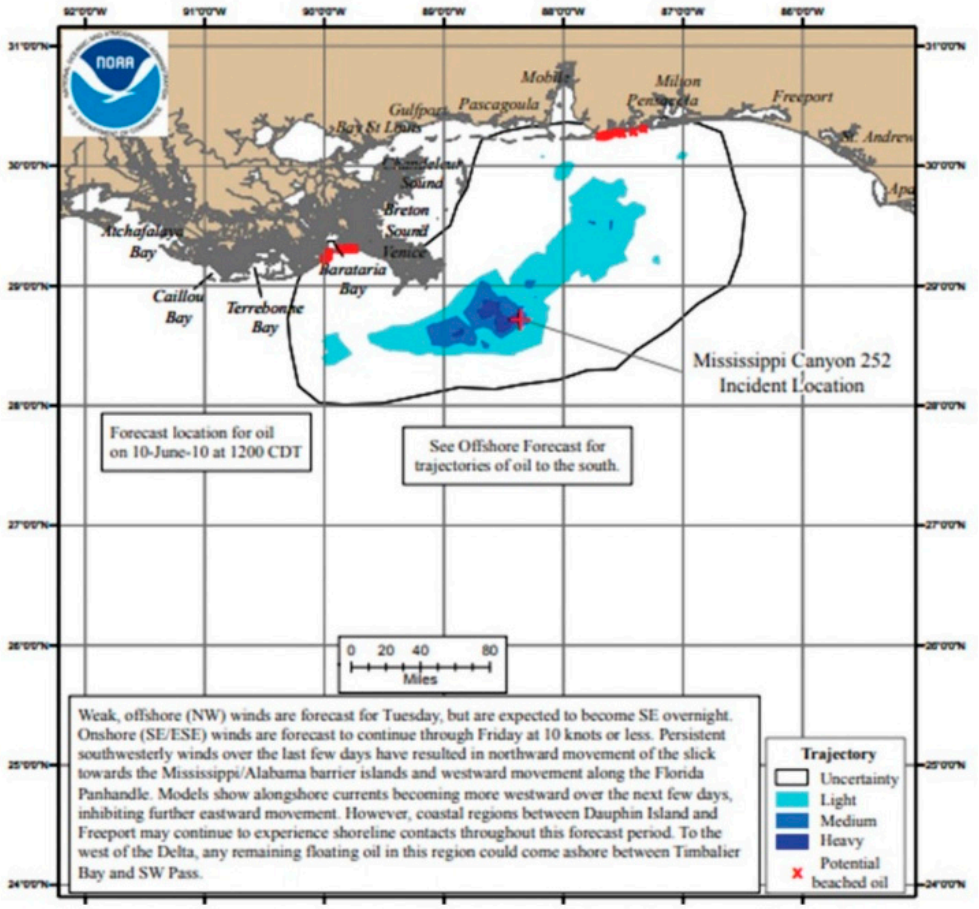

Figure 12. BP oil spill trajectory (NOAA, 7 June 2010) [8].

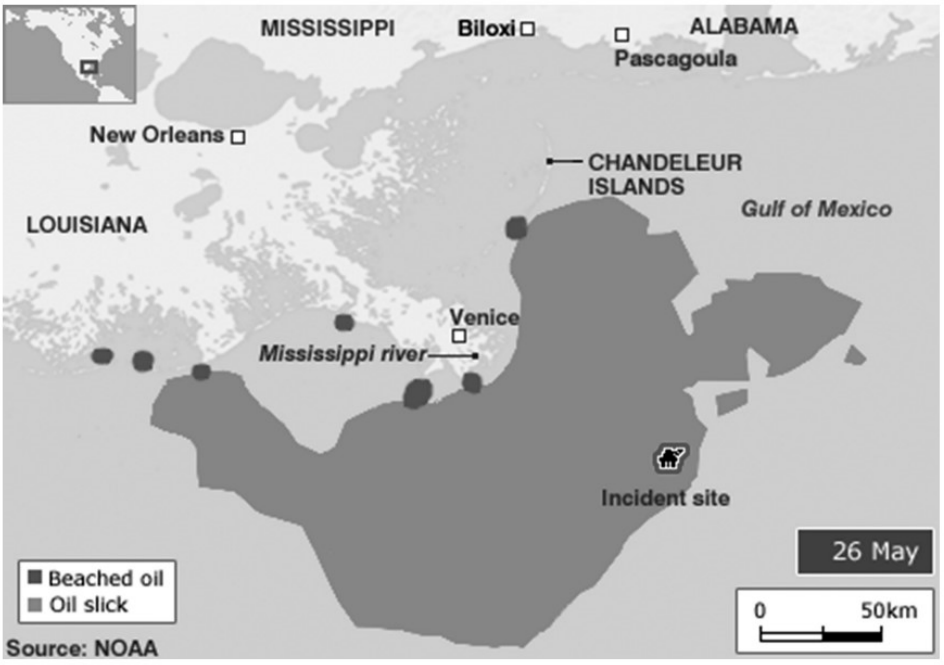

Figure 13. Trajectory of spill as simulated by NOAA 36 days after the accident on 26 May 2010 [8].

3. Recent Publications on Oil Spill Modeling

The volume of published information on oil spill modeling is extensive, and the recommended models often vary by region. A comprehensive review of all the literature is beyond the scope of this paper; however, this section briefly introduces a few recently published studies.

Keramea et al. (2021) provided a comprehensive comparison of 18 oil spill models, highlighting their features, characteristics, and applications across various scenarios [29]. Atodiresei et al. (2025) explored the application of a general NOAA operational model to simulate and analyze oil spill dynamics in the Black Sea [30]. Kvocka et al. (2021) reviewed oil spill models focused on smaller, but more frequent, spills occurring in rivers [31]. Barreto et al. (2021) [32] compared two models—the Coupled Model for Oil Spill Prediction (CMOP) and the Oil Spill Contingency and Response Model (OSCAR)—against experimental data from the Deep Spill project in the Helland Hansen region of the Norwegian Sea. Their comparison demonstrated the capability of both models to simulate the general trajectory of the deep-water plume as well as the surface slick [32].

In his state-of-the-art review of oil spill modeling and future directions, Spaulding (2017) concluded that advanced models increasingly incorporate detailed hydrocarbon composition for more accurate oil characterization [33].

One of the largest oil spills in Brazil, involving approximately 5000 tons of oil, occurred in the second half of 2019. Lamos et al. [34] conducted simulations of oil spills from tanker ships using the Oil Spill Contingency and Response (OSCAR) model. Their results demonstrated how a leak from a ship could impact the Brazilian coastline.

Wang and co-workers developed a three-dimensional numerical model to simulate the movement of oil spills at sea [35]. In this model, the oil spill is represented as a collection of numerous particles, each moving in different directions. The particles drift across the sea surface due to currents and waves and move vertically due to buoyancy forces. The model assumes that 100 oil particles are released every hour, with numerical calculations performed using a 15 min time step over an eight-day period. The model accounts for three weathering processes: evaporation, dissolution, and emulsification. It was applied to the oil spill incident in the Bohai Strait, China, yielding satisfactory results.

Chiu et al. (2021) [36] demonstrated how the integration of numerical tools and observational data can be used to predict wind speed and direction. Their model incorporated wind data from the National Centers for Environmental Prediction (NCEP), meteorological stations, and simulated data from the General NOAA Operational Modeling Environment (GNOME). The model was applied to Taiwan's coastal areas under open sea conditions, as shown in Figure 14. Accurate wind speed data is essential for any oil spill model that simulates movement on the sea surface [36].

Nasr and Smith carried out computer simulations of oil spills in four environmentally sensitive areas along the Egyptian coast. Their study highlighted that key physical and transport properties of oil significantly influence response strategies and cleanup operations [37].

In recent years, the use of machine learning (ML) algorithms and Artificial Neural Networks (ANN) for oil spill detection, prediction, and vulnerability assessment has been explored by several researchers. Studies have demonstrated how ML and AI can be applied to predict oil slick thickness, helping to reduce both time and costs [38,39].

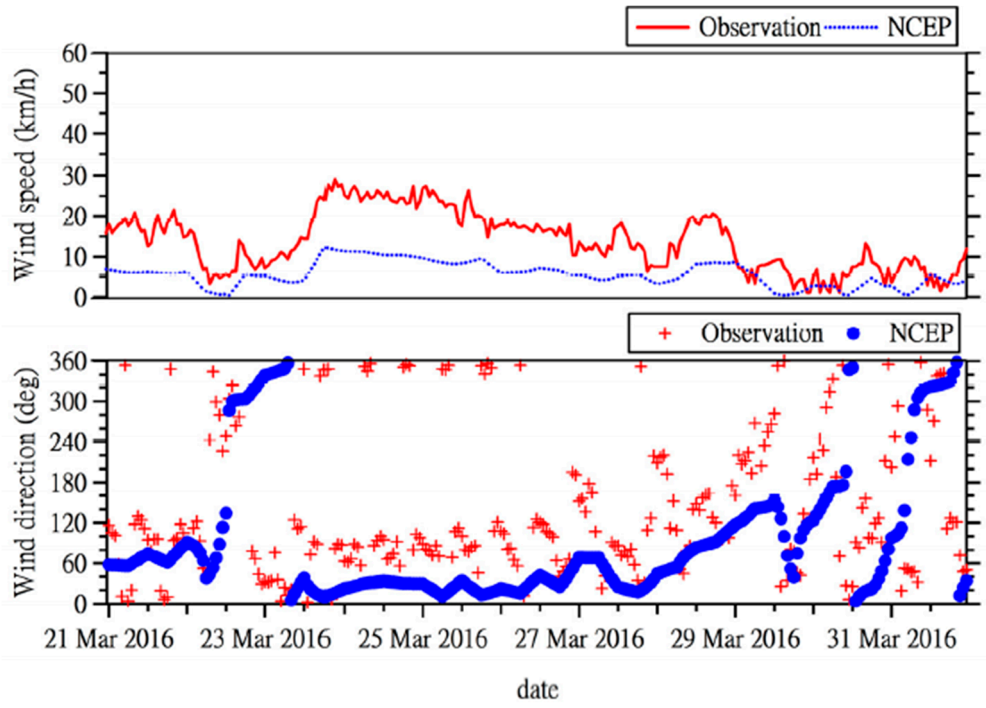

Figure 14. Comparison between predicted and observed wind speed and wind direction. Source: Chiu et al. [36].

4. Summary, Conclusions, and Future Work

In this brief article occurrence and behavior of oil spills were discussed. Two types of models were reviewed: simple and advanced. Simple models predict the amount of oil evaporation, dissolution, spreading, and sedimentation. Advanced models predict oil trajectory and include processes such as oxidation rate, biodegradation, and recovery options. One of the most important parameters in modeling oil jets and plumes is droplet size and its distribution. Advanced models now simulate oil spill behavior in 3D, incorporating wave entrainment and droplet size distribution, enabling prediction of both surface spills and subsea oil jets.

Additionally, applications of some models related to regional oil spill accidents and wind speed prediction models were reviewed. From this study, it can be concluded that key factors in oil spill modeling and simulation are the oil composition, its characteristics, representative model molecules or particles, and the methods used for their characterization. A summary of the models discussed is provided in Table 2.

Table 2. Summary of simple and advanced models for surface and subsurface applications.

Simple Models
This semi-analytical model, developed by Riazi and coworkers [3,16–21], is designed for surface oil spills and is based on the rate of mass transfer of oil components in water and air. It calculates the surface area of the oil slick, its thickness, composition, concentration of dissolved components, and the amounts of oil that have vaporized, dissolved, or sedimented. The model's main advantages are its simplicity and ease of use, as it runs on MS Excel, which is available on virtually every laptop or desktop computer. It accounts for evaporation, spreading, dissolution, and sedimentation, and also predicts the concentration of toxic components in water.

Table 2. *Cont.*

A key feature is its robust characterization scheme, which converts crude oil or petroleum products into an optimal number of pseudocomponents with known physical and chemical properties required by the model. The input data include oil specific gravity (or API gravity) and boiling point (or distillation curve for crude oil), as well as environmental data such as oil and water temperature, wind speed, water salinity, and current speed. The model internally estimates other necessary properties, including vapor pressure, density, interfacial tension, solubility of oil in water, pour point, viscosity, and diffusion coefficients of oil components in both water and air. However, it does not predict the trajectory or movement of oil spill components, nor does it include chemical processes such as biodegradation and oxidation.
Advanced Models
TAMOC Model The Texas A&M Oilspill Calculator (TAMOC), developed by Professor Scott Socolofsky and his team at the Department of Civil Engineering, is currently integrated into NOAA's oil spill modeling system, GNOME. To date, TAMOC offers one of the most comprehensive feature sets among oil spill models. It includes an equation of state and its own database. Input parameters for TAMOC include water current velocities, water temperature and salinity, reservoir fluid composition, gas-to-oil ratio (GOR), location, time, date, longitude and depth of the oil release point, initial jet flow rate, exit diameter, vertical inclination, fluid temperature, fluid phase, viscosity, and interfacial tension with seawater. Source: https://engineering.tamu.edu/news/2018/10/Oilspil-model-developed-at-TAMU-will-inform-decisions-in-the-future.html (accessed on 5 July 2025).
NOAA Model The General NOAA Operational Modeling Environment (GNOME) suite, developed by NOAA, is a publicly available oil spill response tool used by researchers and academic institutions. GNOME incorporates the TAMOC model and utilizes NOAA's own oil database, which contains physical and chemical properties of crude oils and petroleum products. This allows for accurate simulation of environmental behaviors such as emulsification and interaction with chemical dispersants. The NOAA-GNOME trajectory model uses data on wind, ocean currents, oil type, and water turbulence to simulate oil spill movement. The model visualizes oil trajectory as an animation composed of swarms of dots, each representing a portion of the oil volume. Source: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/gnome-suite-oil-spill-modeling.html (accessed on 5 July 2025). GNOME Suite for Oil Spill Modeling | response.restoration.noaa.gov
OpenDrift Model OpenDrift is a Lagrangian particle-tracking model developed by the Norwegian Meteorological Institute. It is user-friendly, fast, and easy to set up on both Mac and Windows platforms. Designed for daily operational use, OpenDrift does not require prior experience with Python, making it accessible to a wide range of users [40].

Table 2. *Cont.*

OSCAR Model The Oil Spill Contingency and Response (OSCAR) model is a 3D simulation tool developed by SINTEF in Norway. It is based on both laboratory experiments and field data, including data from Arctic regions. OSCAR models oil particles transported by currents, wind, and turbulence, and accounts for evaporation, dissolution, and dispersion. It supports both surface and subsurface releases—whether short-term or continuous—and includes advanced features such as modeling oil in ice-covered waters, tracking subsurface gas releases, and assessing biological impacts on marine life. Source: https://www.sintef.no/globalassets/sintef-industri/faktaark/miljoteknologi/oscar-fact.pdf (accessed on 5 July 2025).
OpenDrift-TAMOC Model OpenDrift-TAMOC is a hybrid model that combines the capabilities of OpenDrift and TAMOC, developed by Kotzakoulakis et al. [24]. While it enhances subsurface plume dynamics, it currently does not model sedimentation or oxidation processes.
These advanced models support more accurate predictions of oil spill behavior and improve response efficiency during major subsea blowouts. TAMOC and GNOME, in particular, offer the most complete set of features—such as inclusion of an equation of state—while remaining free and open source, making them excellent platforms for future development and extension.

Simple models can be expanded to include all weathering processes listed in Table 1. In advanced models, characterization methods can be improved by employing component-based models with hydrocarbon types, which provide concentration profiles of toxic compounds in the water column, sea surface, and air. Furthermore, the use of machine learning (ML) and artificial intelligence (AI) in both advanced and simple models can be explored. Further challenges in oil spill modeling are discussed by Kramea et al. [41].

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Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
API	American Petroleum Institute
BP	British Petroleum
DWH	Deepwater Horizon
GIS	Geographic Information System
GNOME	General NOAA Operational Modeling Environment
GOM	Gulf of Mexico
LNG	Liquified Natural Gas
ML	Machine Learning
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
OSCAR	Oil Spill Contingency and Response
SAR	Synthetic Aperture Radar
TAMOC	Texas A&M Oilspill Calculator

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