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SIMULATION OF OIL SPILL TRAJECTORY AND FATE
AT THE SOUTHERN ENTRANCE OF THE SUEZ CANAL, RED SEA, EGYPT

Abstract

The Suez Canal suffers from heavy maritime traffic, especially oil tankers, due to its strategic location between the Mediterranean and the Red Sea. As a result, it is prone to accidental oil spills, which might obstruct the maritime lane via the canal and severely harm the marine and coastal ecosystems. This study aims to forecast an oil spill trajectory and fate under the influence of different wind regimes using the General NOAA Operational Modeling Environment (GNOME) and the Automated Data Inquiry for Oil Spills (ADIOS2) models to define the potentially affected regions. Hence, four scenarios were simulated, assuming a spill of one thousand metric tons of Arabian light crude oil into the seawater about two kilometers from the Suez Canal's southern entrance. The results highlight that wind direction and sea currents substantially affect the movement of oil spills. The trajectory maps show that the north-west wind forces the spilled oil to move toward the southeast direction, threatening the navigation lane through the Suez Canal and about 38 km of beaches south of the canal, which has several vital projects such as the Ayoun Mousse power plant and a lot of resorts. In the case of northern winds, the oil moved south in the center of the Gulf, which may allow response teams more time to clean up the spill. However, in the case of north-east winds, the oil drifted southwesterly and threatened the Green Island and western shores of the Gulf, which has many tourist villages. About a quarter of the oil evaporated, and more than two-thirds of the oil emulsified in all four scenarios. For the first time, this study has provided an understanding of oil spill forecasting and trajectory modeling for the Suez Canal's southern entrance. Also, it can be considered a prediction tool for Egypt's policymakers and Suez Canal Authority (SCA) to develop adequate and practical strategies to mitigate crude oil spill consequences.

Keywords: Oil spill, Modeling, Scenarios, GNOME, ADIOS, Suez Canal, Gulf of Suez

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МОДЕЛИРОВАНИЕ ТРАЕКТОРИИ И ПОСЛЕДСТВИЙ РАЗЛИВА НЕФТИ
У ЮЖНОГО ВХОДА СУЭЦКОГО КАНАЛА, КРАСНОЕ МОРЕ, ЕГИПЕТ

Аннотация

Суэцкий канал страдает от интенсивного морского судоходства, особенно нефтяных танкеров, из-за его стратегического положения между Средиземным и Красным морями. В результате он подвержен случайным разливам нефти, которые могут заблокировать морской путь через канал и нанести серьезный ущерб морской и прибрежной экосистемам. Это исследование направлено на прогнозирование траектории и последствий разливов нефти под влиянием различных ветровых режимов с использованием общей среды оперативного моделирования NOAA (GNOME) и моделей автоматизированного запроса данных для разливов нефти (ADIOS2) для определения потенциально пострадавших регионов. Таким образом, были смоделированы четыре сценария, предполагающие разлив 1000 метрических тонн аравийской легкой сырой нефти в морскую воду примерно в 2-х км от южного входа в Суэцкий канал. Результаты показывают, что направление ветра и морские течения существенно влияют на перемещение разливов нефти. Карты траектории показывают, что северо-западный ветер заставляет разлившуюся нефть двигаться в юго-восточном направлении,

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угрожая навигационному пути через Суэцкий канал и около 38 км пляжей к югу от канала, где есть несколько жизненно важных проектов, таких как Ayoun Mousse электростанция и много курортов. В случае северных ветров нефть перемещалась на юг в центр залива, что может дать группам реагирования больше времени для ликвидации разлива. Однако в случае северо-восточных ветров нефть дрейфовала на юго-запад и угрожала острову Зеленый и западным берегам залива, где расположено множество туристических поселков. Около четверти нефти испарилось, и более двух третей нефти эмульгировалось во всех четырех сценариях. Это исследование впервые дало представление о прогнозировании разливов нефти и моделировании траектории разлива на южном входе в Суэцкий канал. Кроме того, его можно рассматривать как инструмент прогнозирования для политиков Египта и Управления Суэцкого канала (SCA) для разработки адекватных и практических стратегий по смягчению последствий разливов сырой нефти.

Ключевые слова: разлив нефти, моделирование, сценарии, GNOME, ADIOS, Суэцкий канал, Суэцкий залив

1. Introduction

Worldwide demand for crude oil continues to increase, despite the current attempts to convert to sustainable energy sources and renewable fuels [1, 2]. Marine transport is the most common method for transporting crude oil globally, which has economic and environmental benefits [3, 4]. As a result, the number of ships, the intensity of traffic, and port operations have increased. Hence, the possibility of accidents resulting in oil spills will increase [4, 5]. According to the International Tanker Owners Pollution Federation (ITOPF) [6], the total crude oil spilled into the marine environment due to tanker incidents in 2021 was approximately 10,000 tons. Oil spills are considered the most critical form of marine pollution [7—9]. Thus, the oil spill incidents remain a concerned subject of research for efficient prevention and response measures. Simulating oil spill movement and behavior is essential before beginning any response plan [10, 11].

When oil is spilled into the marine environment, it undergoes a series of physical and chemical changes known as weathering [12—14]. The major oil spill weathering processes are evaporation and emulsification, which depend on the type of oil spilled and environmental conditions during and after the spill. [15—17]. Evaporation is the leading actor in removing oil from the sea surface. At the same time, emulsification leads to persistence and an increase in the volume of pollutants [18]. Thus, predicting the behavior of spilled oil enables selecting the most efficient and effective response and mitigation techniques [19]. Modeling hypothetical oil spills before they occur is necessary to assess the likelihood of an oil spill damaging vulnerable resources in water areas and coasts, to determine the time available for deploying the forces and means of an oil spill containment and response system, to evaluate options for strategies for using technical means [20].

Oil spill modeling is an effective tool that can anticipate a spill's trajectory, estimate the time it will take for the oil to reach certain regions of interest, and assess the spill's status once it gets to the modeled sites [1, 21, 22]. Various efforts have been made worldwide to model the oil spill movement in real and hypothetical incidents. Simulation of the oil spill has been carried out by different software. Some of the most extensively used oil spill models capable of anticipating the direction and outcome of oil spills are as follows; General NOAA Operational Modeling Environment (GNOME) [23—26], Delft3D-PART [27], OILMAP [28], Particle Transport Model (OILTRANS) [29], OpenOil [30, 31], and Automated Data Inquiry for Oil Spills (ADIOS2) [32, 33].

The Suez Canal is one of the main crucial shipping routes for Egypt and the entire globe. The possibility of oil spill accidents in Egyptian water has increased due to the shipping traffic that passes through the Suez Canal to the Mediterranean Sea [34]. On the 5th of August, 2014, Egyptian President Abdel Fattah El-Sisi declared the start of Egypt's new Suez Canal project. Consequently, canal traffic increased from 18,830 vessels in 2020 to 20,694 in 2021, or more than 56 per day [35]. Due to this heavy traffic, the canal is prone to accidental oil spills that might obstruct the maritime route and harm the marine ecosystem. According to Kostianaia et al. [34], the Suez Canal has already seen many oil spill incidents. As a result of oil tanker accidents, about 4,000 tons of crude oil leaked in 2004, and 9,000 tons were spilled in 2006 [36]. Despite the high shipping activities and the potential of being exposed to oil spills in Egypt's waters, only a few published research papers have predicted the trajectory of spills [36—40]. Moreover, there is no existing reference for predicting oil spill movement in the area under investigation (the Suez Canal's southern entrance), making this the first research of its sort. The study aims to simulate an assumptive oil spill incident at the Suez Canal's southern entrance under the influence of different wind regimes, primarily to define the potentially affected regions.

2. Study area

The Suez Canal is an artificial waterway of 193 km running from Port Said north to the Gulf of Suez south, thus connecting the Mediterranean and the Red Seas, as shown in Fig. 1. It is one of the most vital and heavily used waterways globally; navigation started on the 17th of November, 1869 [34]. According to the Suez Canal Authority [41], the canal accounts for around 10 % of worldwide marine traffic and provides Egypt with much-needed foreign cash. In 2021, the canal transported almost 1.27 billion tons of cargo, a 13 % increase over the previous year and the highest amounts ever
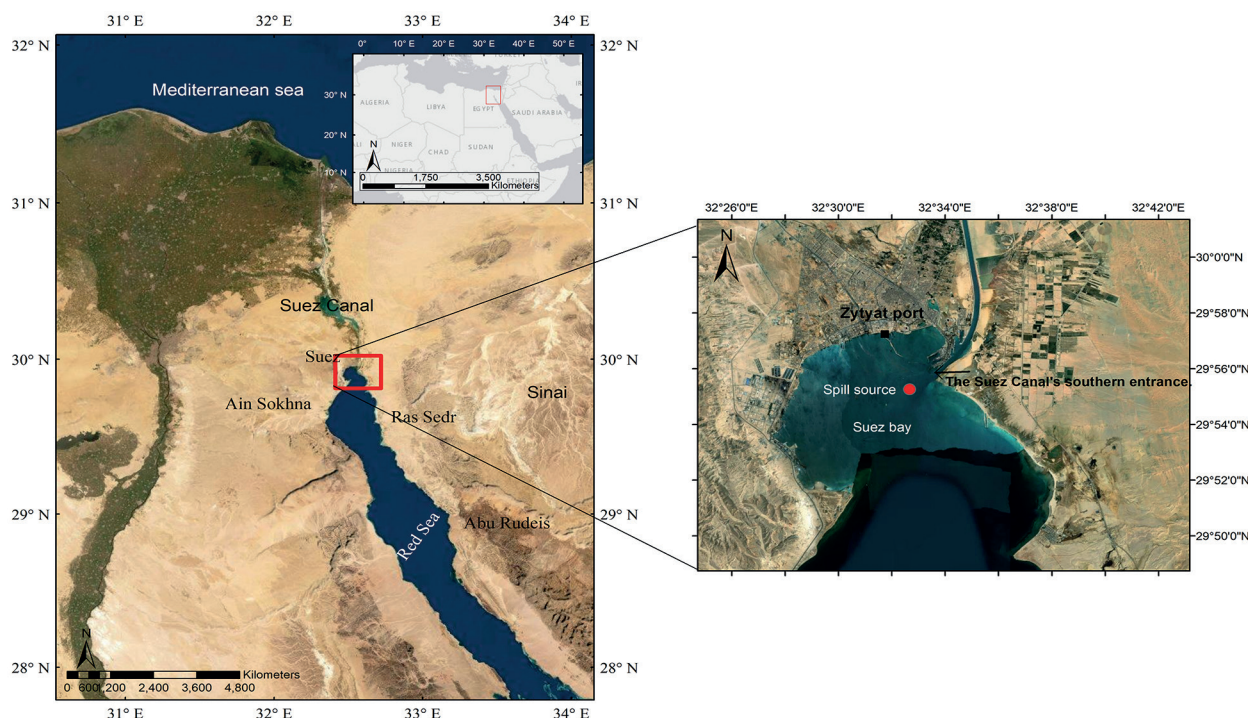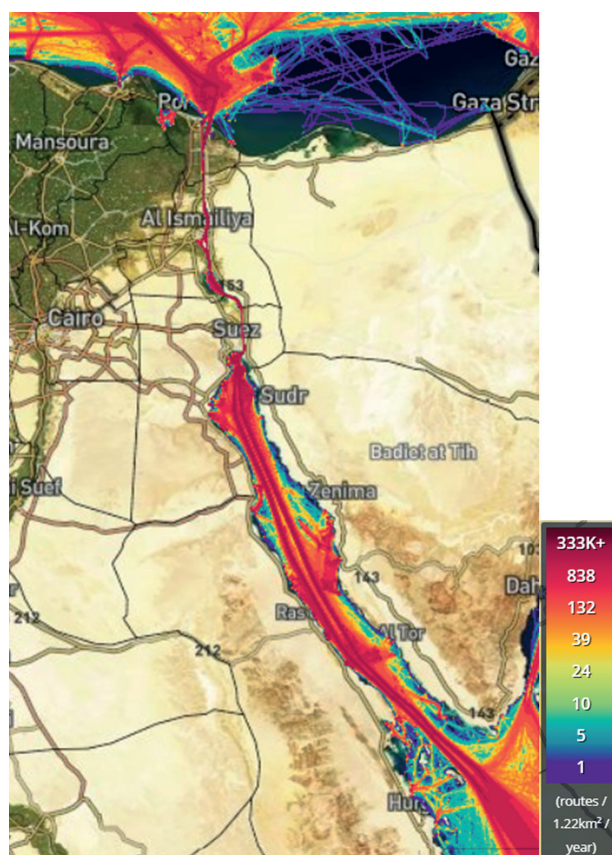
Fig. 1. The Suez Bay and Canal map showing the hypothetical oil spill source as a big red dot off the southern entrance of the Suez Canal and Zaytyat Port

recorded. Fig. 2 shows marine traffic density in the Gulf of Suez and Suez Canal for all ship types in 2021 [42]. In the present study, an assumptive oil spill is considered in the Suez Bay, off the southern entrance of the Suez Canal Fig. 1. The Suez Bay, which represents the south entrance of the Suez Canal, is a shallow extension of the Gulf of Suez, roughly

twisted in shape, with its central axis in the NE-SW direction [43]. Therefore, the Bay is always congested with cargos and tankers awaiting transit through the canal to the Mediterranean, which may result in oil leak accidents. Another factor contributing to the probability of an oil spill in the region is the Zytyat port. The Port is one of Egypt's oldest and largest specialty ports. It is utilized by Suez oil corporations to accept oil tankers laden with petroleum and gas from the Red Sea and South Sinai Governorate [44].

3. Data used and methodology

In this study, two software have been used, General NOAA Operational Modeling Environment (GNOME) and Automated Data Inquiry for Oil Spills (ADIOS2). These models can identify the target area impacted by pollutants and calculate the weathering processes (evaporation and emulsification) [23, 45]. The results of these models are in the form of images, graphics, movies, and data files compatible with GIS (geographic information system) for further analysis [16]. These data could be analyzed using various workflows for further investigation [46]. Fig. 3 represents this study's input and output flowchart for trajectory and behavior modeling.

Fig. 2 Heavy traffic at the Gulf of Suez and Suez Canal, source marine traffic [42]
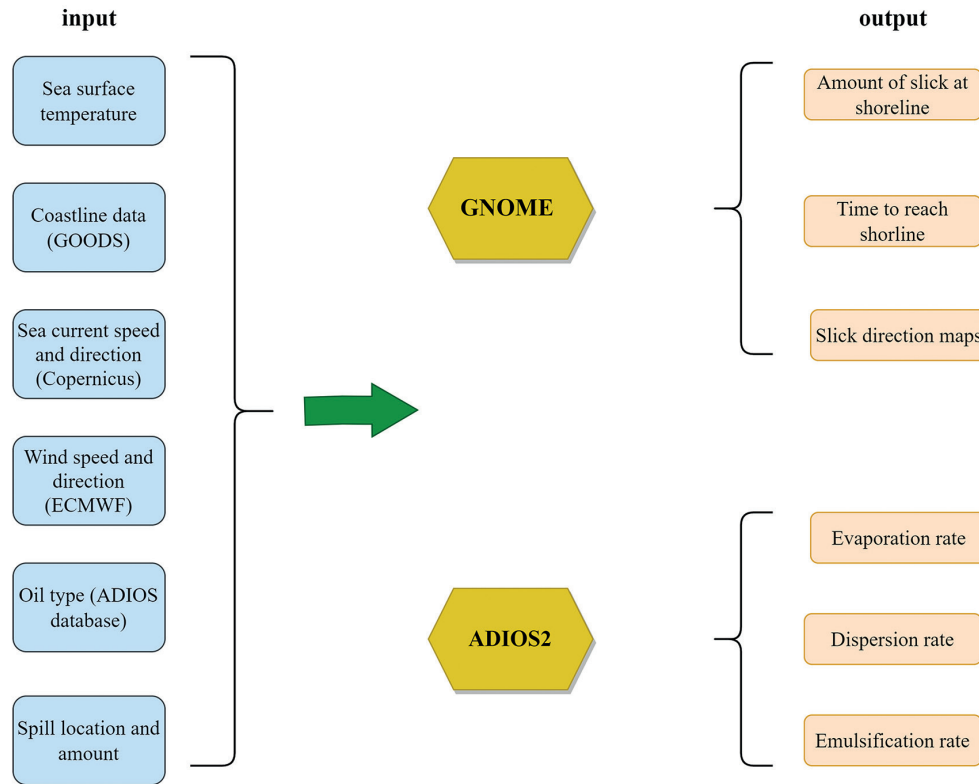
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input

output

Sea surface temperature

Coastline data (GOODS)

Sea current speed and direction (Copernicus)

Wind speed and direction (ECMWF)

Oil type (ADIOS database)

Spill location and amount

GNOME

Amount of slick at shoreline

Time to reach shorline

Slick direction maps

ADIOS2

Evaporation rate

Dispersion rate

Emulsification rate

Fig. 3. A flowchart of input and output for oil spill trajectory and fate modeling

3.1. Oil-spill trajectory simulation

The General National Oceanic and Atmospheric Administration Operational Oil Modeling Environment (GNOME) model was developed by NOAA's Hazardous Materials Response (HAZMAT) and debuted on the 16th of March, 1999 [47]. The GNOME model is two-dimensional and more generalizable than other models and requires fewer parameters as input [48]. This two-dimensional model is frequently used in marine, coastal, and riverine environments to predict the movement of oil slicks [25, 48]. GNOME's input data set contains coastline data, spill location, oil type, spill volume, and direction of the wind and sea currents. In addition, the model provides georeferenced trajectory output that may be used as an input to GIS (geographic information system) tools [24]. The GNOME model uses the Euler-Lagrange particle tracking method to monitor oil spill movement [49]. This method considers the oil slick to be a group of particles. As each particle passes through water, its path through the liquid is computed. The time-dependent velocity and direction of each particle may also be calculated. Due to diffusion and evaporation, oil conditions can be monitored in real-time [33, 50]. The GNOME model includes a refloating algorithm that empirically describes the adhesiveness of the oil to the shoreline; a "half-life" parameter can be set by the user It is a function of substrate porosity, the presence or absence of vegetation, the inherent stickiness of the oil, and other physical properties and processes of the environment as well. These different parameters have been lumped together in a single parameter, "half-life". This is the number of hours in which half of the oil on a given shoreline is expected to be removed if (1) there is an offshore wind or diffusive transport and (2) sea level is at the same level, or higher, than the level of the oil when it was beached [23, 47]. Samaras et al. [51] present half-life values for different beach types ranging from zero for seawalls and concrete to 124 sheltered sand or gravel beach. In this study we used a half-life value of 24 h for GNOME simulations, which is representative of a sand or a gravel beaches".

In this study, we adopted the GNOME modeling tool because of its record of practical deployment and validation against real-world environmental disasters and its widespread use across organizations [1, 52]. Moreover, as shown by multiple studies, GNOME findings for many scenarios demonstrated a high degree of consistency between model simulation, satellite data, and experimental observations [25, 53]. Consequently, the Marine Emergency Mutual Aid Centre has advised that oil spills in the Arabian Gulf be simulated using the GNOME model [54].

3.2. Oil-spill weathering simulation

The Automated Data Inquiry for Oil Spills (ADIOS2) is an oil spill model developed by National Oceanic and Atmospheric Administration (NOAA). It stimulates the processes involved in oil weathering, including evaporation and emulsification [45]. The model input data are the oil type and amount, seawater temperature, wind, and current data. ADIOS2 blends a library of around 1,000 oils with a short-term oil fate and cleaning model to estimate how long spilled oil will persist in the marine environment and develop cleanup techniques. Computed ADIOS2 data combines real-time weather data (wind speed) with chemical and physical property data from its oil library [46]. The model codes are available for different water areas: open sea, nearshore waters, semi-confined coastal waters, estuaries, rivers, lakes, and reservoirs [55].

3.3. Data sources

This study's spill scenarios comprise both actual and hypothetical environmental parameters. The actual wind parameters were obtained in NetCDF file format from the European Centre for Medium-Range Weather Forecasting (ECMWF) Reanalysis (ERA5)[1]. The hypothetical wind parameters are the north-west NW, north N, and north-east NE with a constant speed of 4 m/s. We selected these parameters based on the Egyptian meteorological authority [56]. The actual currents parameters were obtained from GLOBAL_ANALYSIS_FORECAST_PHY_001_024 Global Ocean 1/12° Physics Analysis and Forecast updated Daily) in a NetCDF format, a format suitable for GNOME[2].

The GNOME requires that the file describing the coastline be in a bna format, which is available from the High-resolution Shoreline (GSHHS) database using the GNOME Online Oceanographic Data server (GOODS). The GSHHS is a high-resolution geography data set amalgamated from two databases: World Vector Shorelines (WVS) and CIA World Data Bank II (WDBII) [16, 57][3].

4. Model formulation and assumptions

A hypothetical oil spill caused by a tanker accident in the Suez Bay at the southern entrance of the Suez Canal is considered for the present study. This possible oil spill source is in the shipping lane about 2 kilometers from the shoreline, as shown in Fig. 1. One thousand metric tons of Arabian light crude oil is assumed to have spilled on the 10th of February 2021 at 12.00 am. The Arabian Light crude oil selection was based on the frequency with which tankers carry it via the Suez Canal and the Sumed pipeline [37]. Additionally, the ADIOS2 Model library includes a parameter database for this oil type and the characteristic constants necessary to solve the constitutive equations Table 1.

The GNOME and ADIOS2 models were used to simulate the trajectory and behavior of the spill. As previously mentioned, the GNOME and ADIOS2 input data sets contain coastline data, wind data, sea currents data, oil spill location, oil type, oil amount, and seawater temperature. This study's spill scenarios comprise both actual and hypothetical environmental parameters. The actual wind data was downloaded from the ECMWF Reanalysis ERA5, while sea currents data was from Copernicus. The wind speed is assumed to be constant at 4 m/s, which is the average scalar speed for February in Suez, and the wind direction is manipulated to represent the three predominant wind directions: the NW, accounting for 22.4 % of the frequency; the N (17.3 %); and the NE (7.0 %) [36]. Seawater temperature was extracted from previous studies, where the average seawater temperature in winter is 18.7 °C [58].

Table 1

Arabian light crude oil characteristics (ADIOS2 oil library database)

Parameter	Quantity
API (degree)	33.4
Density	0.878 g/cc at 0 °C
Viscosity	12 cSt at 0 °C
Pour point	−53 °C
Adhesion	0.14 g/m^2
Aromatic	39 weight%

API, American Petroleum Institute.

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[1] https://www.ecmwf.int/
[2] https://resources.marine.copernicus.eu/product download/GLOBAL_ANALYSIS_FORECAST_PHY_001_024
[3] https://gnome.orr.noaa.gov/goods/tools/GSHHS/coast_subset

Table 2

GNOME model scenarios with various parameters

Scenario	Spill location	Volume of spill	Seawater current	Wave speed and direction
Scenario 1	Late: 29.9214 N Long:32.5493 E	1000 metric tons	Variable	Variable
Scenario 2	Late: 29.9214 N Long: 32.5493 E	1000 metric tons	Variable	4 m/s from NW
Scenario 3	Late: 29.9214 N Long: 32.5493 E	1000 metric tons	Variable	4 m/s from N
Scenario 4	Late: 29.9214 N Long: 32.5493 E	1000 metric tons	Variable	4 m/s from NNE

Coastline data was obtained from the GSHHS database by the GOODS server. The simulation period was 72 h at a step of 0.25 h. The along-current and cross-current uncertainty values for the sea currents data were adjusted to 10 % to accommodate probable currents value uncertainties. According to Zelenke et al. [23], along-current uncertainty is the uncertainty in the forward and backward currents values. In contrast, cross-current uncertainty refers to the left and right direction uncertainty. Four different scenario settings are presented in Table 2.

5. Results

Variable wind and sea current data are used for Scenario 1. The simulation for the model started at 12:00 am on the 10th of February 2021. One thousand metric tons of Arabian light crude oil hypothecated to have leaked from the vessels at the spill location. The spill is represented in terms of dots which are either black or red. The black color dots represent the best guess solution, assuming there are no input parameters uncertainties. In contrast, the red dots represent a minimum regret solution that incorporates the uncertainties of wind and sea currents. The red dots on the map show the possible uncertainty of the spill position (more correctly, the contamination area), i.e. not an increase in the actual contamination area, but a possible shift of the "center of mass" of oil spills. The area covered by the "red dots" is not in general associated with a possible increase in the area of the contamination area. This is just the displacement of the black dots in any direction.

The results of Scenario 1 from the GNOME model are displayed in Fig. 4 as maps every six hours. As the simulation started, oil particles drifted in a southeast direction SE. Three hours after the simulation's beginning at 3 am, about 0.84 % (177 metric tons) of the oil started reaching the southern entrance of the Suez Canal and continued
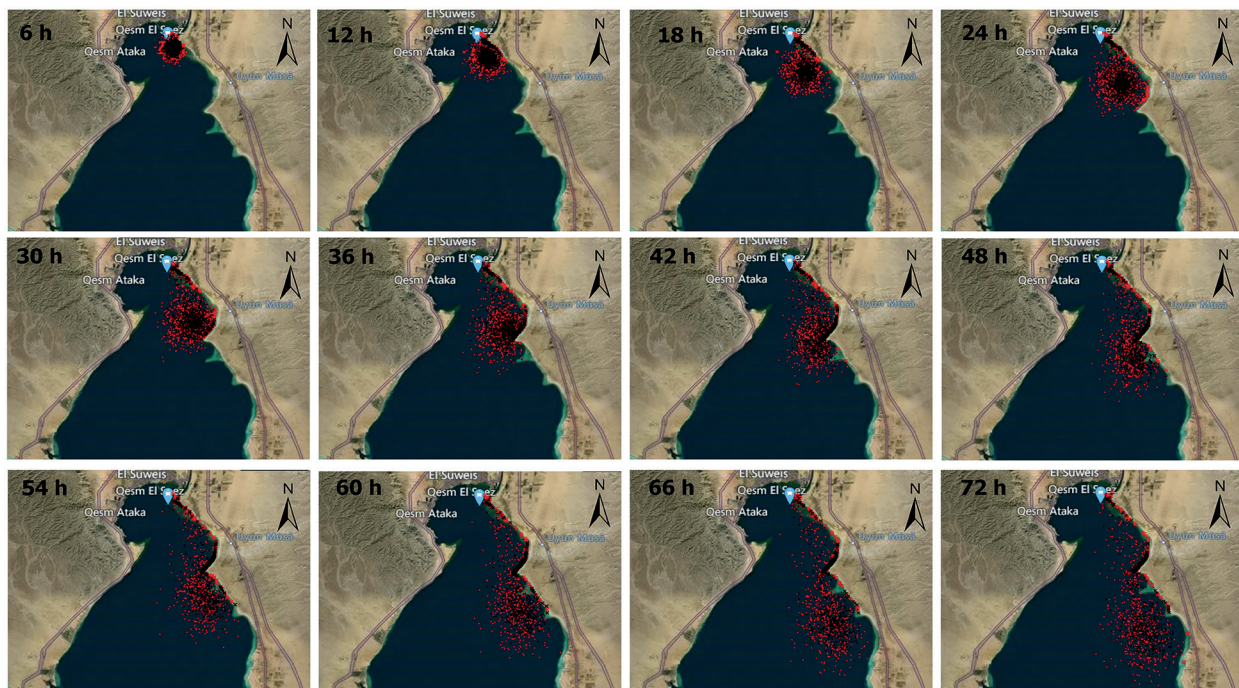

Fig. 4. Oil particle position for Scenario 1 (variable wind and sea currents speed and direction). The black dots represent BGS, and the red dot presents MRS). The spill source is shown as the big blue dot

to accumulate on the eastern side of the Gulf of Suez. After 72 hours, approximately 37.2 % of the oil had covered about 34 kilometers of the east coast of the Gulf of Suez from (29°56'17.50"N32°33'14.24"E to 29°42'29.57"N32°41'20.83"E) for both black dots (best guess) and red dots (minimum regret solution). At the same time, approximately 35.9 % (359 mt) of the oil traveled 30 km from the spill source and remained floating. The evaporation and emulsification processes started immediately after the oil spill. Within 72 hours, around 26 % (260 mt) of the total oil spill had evaporated, and the emulsion water content reached approximately 84.8 %, Fig. 5.

Scenario 2 is simulated with a constant wind speed of 4 m/s from the NW direction and variable sea current. The model is set off on 10.2.2021 at 12:00 am. Here we saw the slick starts to move ESE direction with the best guess and minimum regret coverage area, Fig. 6. In this scenario, beaching started after two hours at 2 am; nearly less than one metric ton of oil was found to be beached along the southern entrance of the Suez Canal. At the end of the simulation,
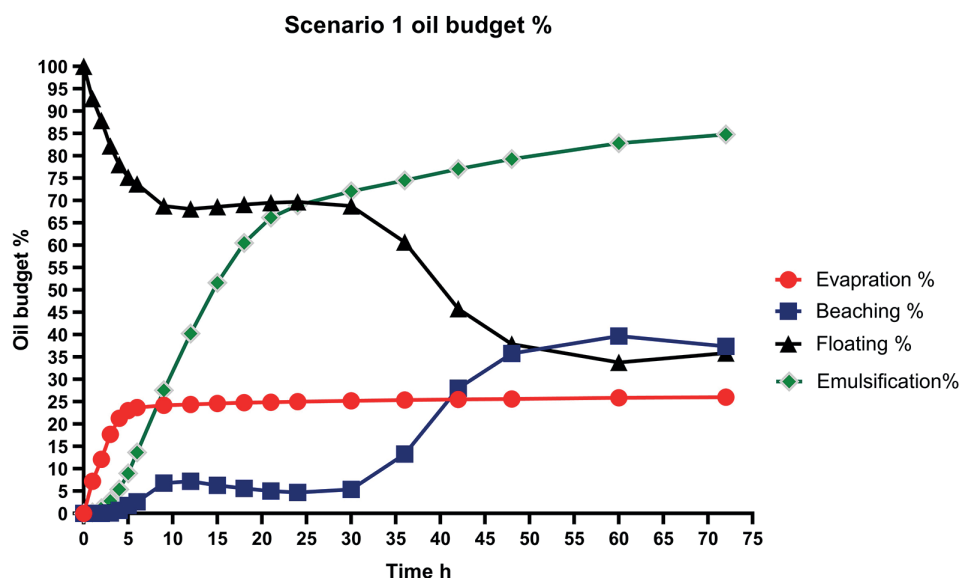

Fig. 5. The spilled oil's evaporation, beaching, floating, and emulsification during the simulation period of Scenario 1
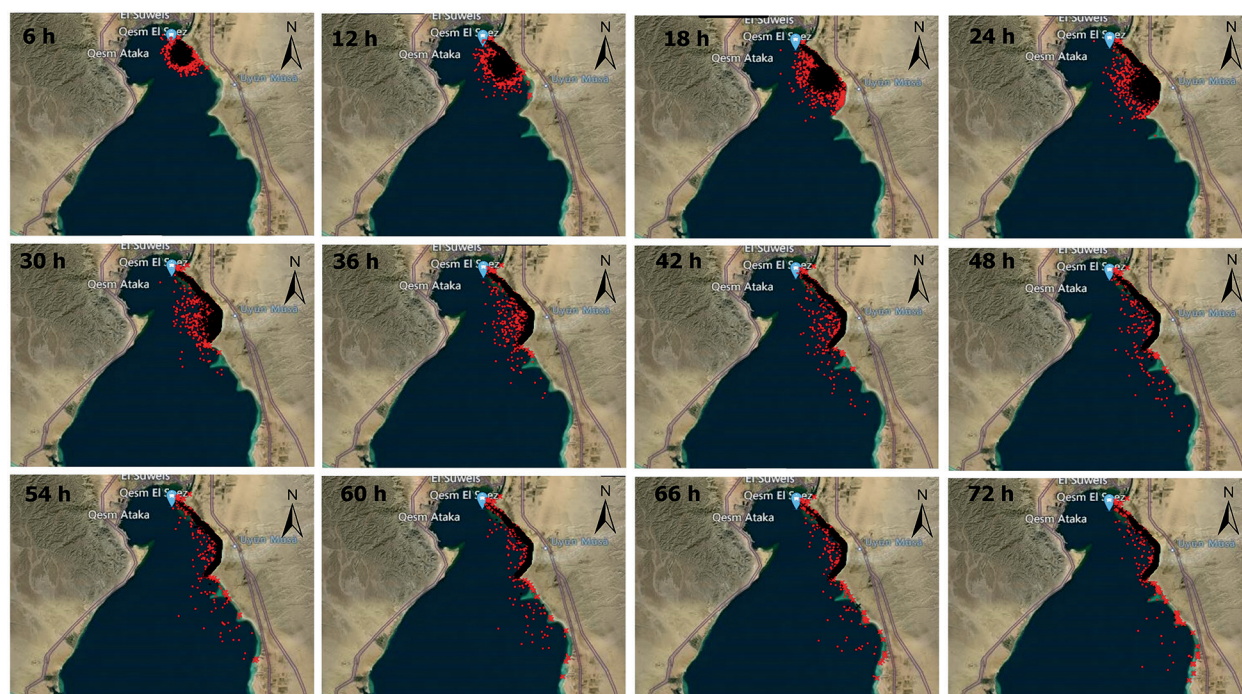

Fig. 6 Oil particle position for Scenario 2 (constant wind speed 4 m/s from NW direction). The black dots represent BGS, and the red dot presents MRS). The spill source is shown as the big blue dot

approximately 70.5 % of the whole oil was beached along the eastern shoreline of the Gulf of Suez, south of the Suez Canal. In this case, Black dots covered about 16.5 km (29°55'46.04"N32°33'36.28"E to 29°48'56.49"N32°35'52.46"E), While Red dots affect more than 38 km (29°56'17.43"N32°33'27.54"E to 29°39'33.62"N32°39'45.01"E). After 72 hours, the evaporation rate was about 25.2 %, and the emulsification amount was 73.3 %, Fig. 7.

In Scenario 3, the simulation is run with a constant wind speed 4 m/s from the N direction. As the simulation started at 12 am, the spill moved in the south direction with black (best guess solution, BGS) and Red (minimum regret solution, MRS) dots, Fig. 8. After 9 hours, a minor amount of 0.1 % of oil reached the eastern and western beaches of the Gulf of Suez. While at the end of the simulation, the majority of the oil, around 73.8 %, stayed floating in the center of the Gulf waters and continued travel in the south direction. After 72 hours, the amount of oil lost due to evaporation reached 25.6 %, and the emulsion water content reached approximately 76.4 %, Fig. 9.

Fig. 7. The spilled oil's evaporation, beaching, floating, and emulsification during the simulation period of Scenario 2

Fig. 8. Oil particle position for Scenario 3 (constant wind speed 4 m/s from N direction). The black dots represent BGS, and the red dot presents MRS). The spill source is shown as the big blue dot
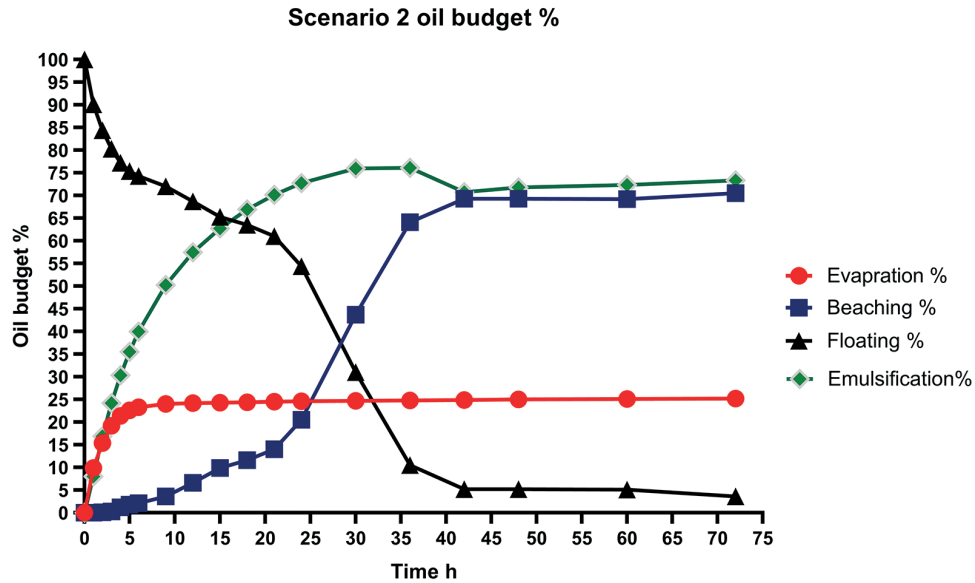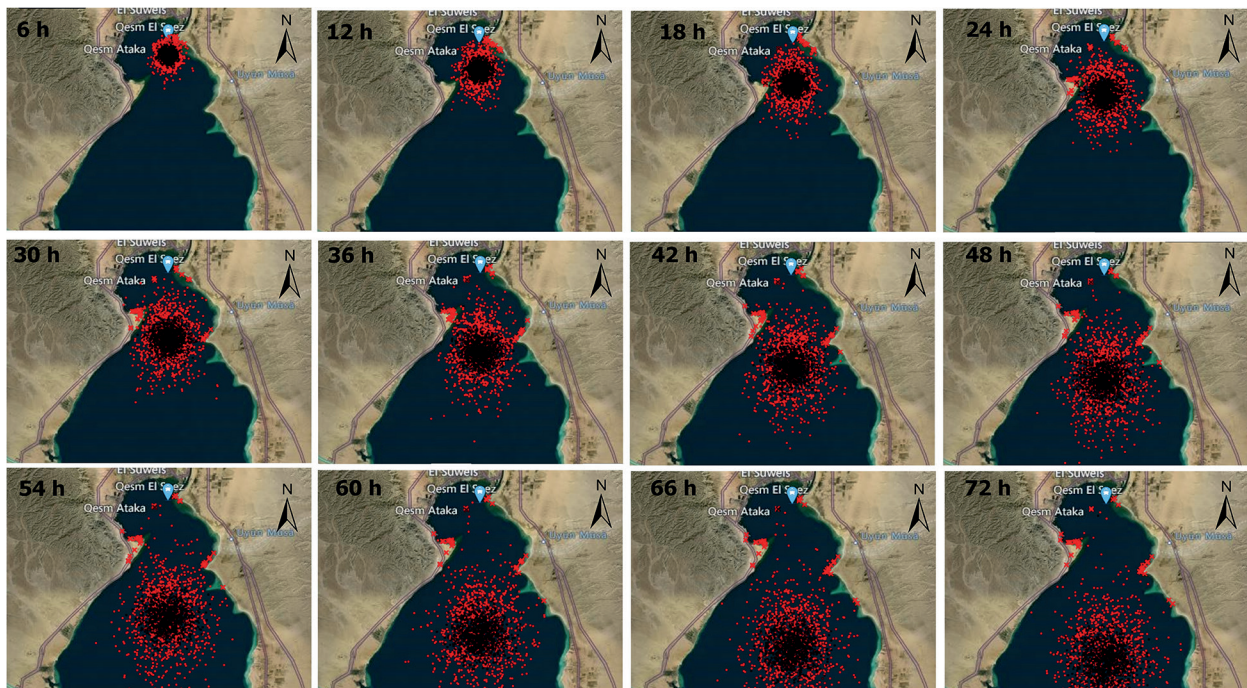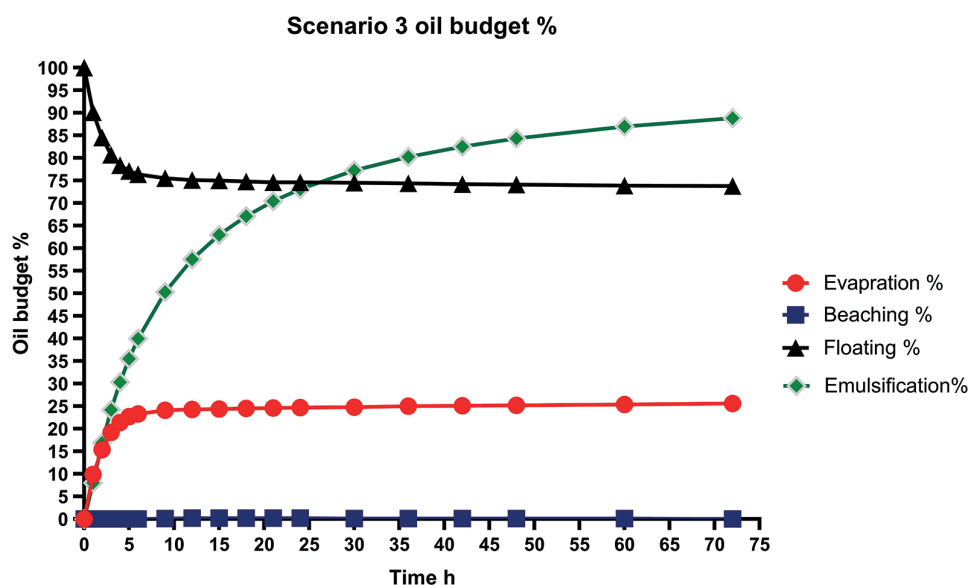
Fig. 9. The spilled oil's evaporation, beaching, floating, and emulsification during the simulation period of Scenario 3

The fourth scenario is simulated with a constant wind speed of 4 m/s from the north-east NE, Fig. 10. As the simulation begins at 12 am, the oil slick starts moving in the southwest direction toward the western coast of the Gulf of Suez. Immediately after 2 hours at 2 am, approximately 1.4 % (140 mt) starts beached to the Green Island, about 2 km from the spill location. After 18 h at 6 pm, the slick traveled about 9 km and reached the western coast of the Gulf of Suez at Al-Adabiya port. After 72 hours, approximately 60.3 % of all spilled oil accumulated on the Green Island and covered about 40 km of the western coast of the Gulf of Suez from 29°54'31.20" N32°27'43.70" E to 29°39'11.66" N32°21'54.20" E for black and red dots. At the same time, approximately13.7 % remained in the water and continued floating. As shown in Fig. 11, the amount of oil lost due to evaporation was about 25.3 % (253 mt), and the emulsion water content reached approximately 80.1 % at the end of the simulation.
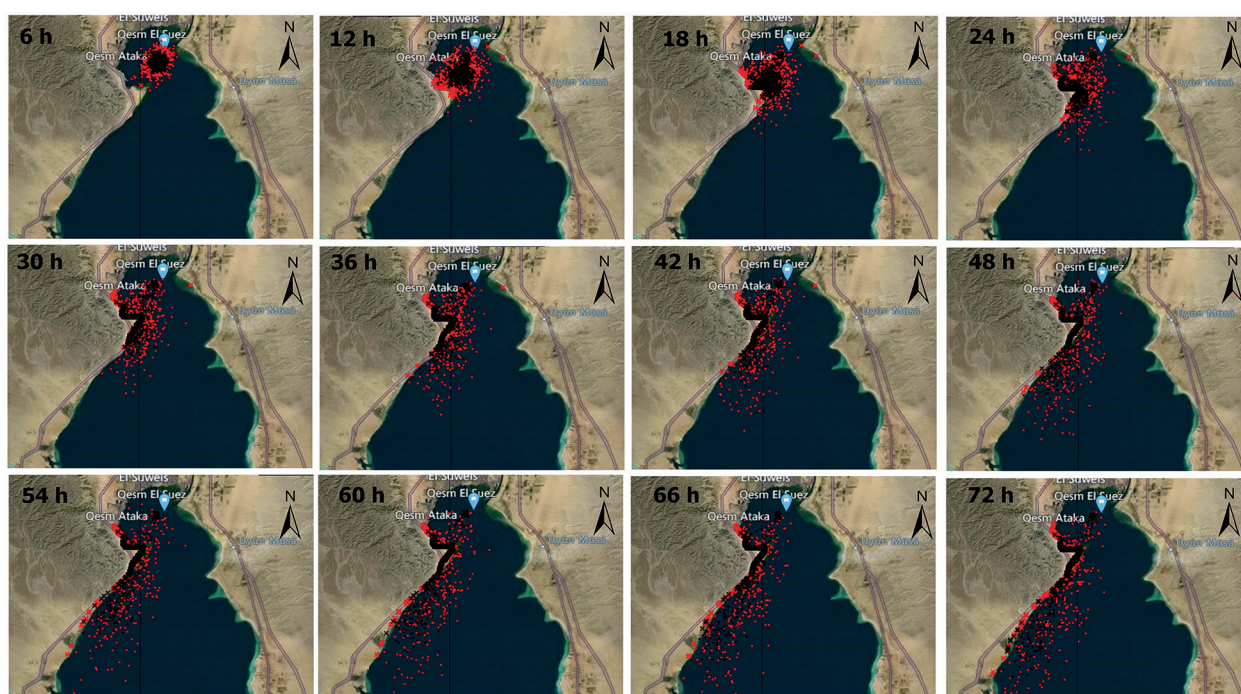

Fig. 10. Oil particle position for Scenario 4 (constant wind speed 4 m/s from NE direction). The black dots represent BGS, and the red dot presents MRS). The spill source is shown as the big blue dot
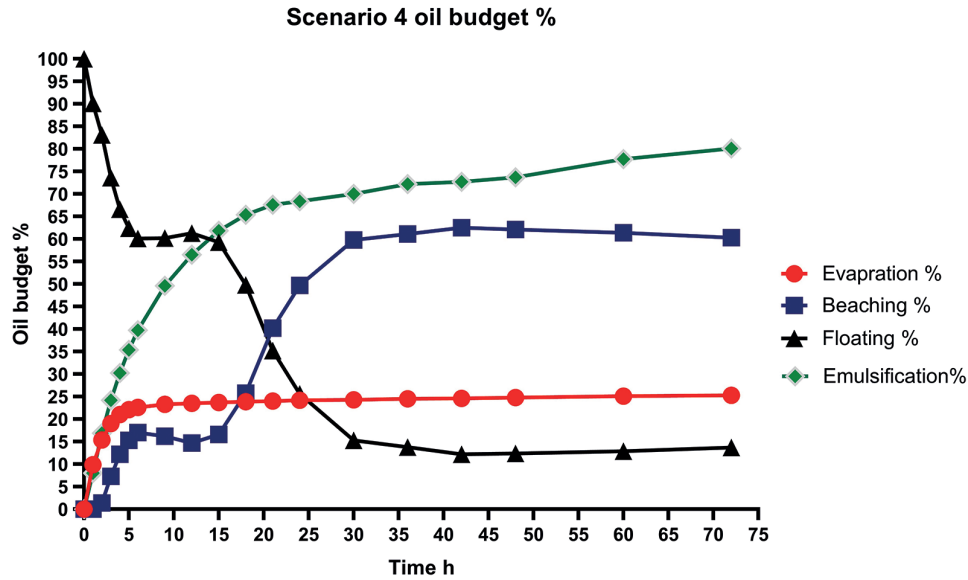
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Scenario 4 oil budget %

Fig. 11. The spilled oil's evaporation, beaching, floating, and emulsification during the simulation period of Scenario 4

6. Discussion

This study simulates four possible oil spill scenarios that may be induced by a vessel accident at the southern entrance of the Suez Canal. Hence, the GNOME trajectory model simulated the oil spill's movement and time to reach the beach. In addition, the Automated Data Inquiry for Oil Spills (ADIOS2) has been utilized to identify how the oil breaks down naturally as it propagates (through evaporation and emulsification).

The trajectory maps in this study show that wind speed and direction significantly affected the movement of spilled oil in all four scenarios. These results are in line with those of previous studies. Numerous prior studies have indicated that the wind speed and direction during and after an oil spill significantly affect the oil's mobility in the marine environment [59–62]. Another potential cause for the flow of the spilled oil in the south direction in all scenarios is that it may be influenced by the predominant southerly movement of the sea currents. According to Frihy [63], sea currents in the Gulf of Suez mainly move southward.

The results show that the spilled oil moved southeast in Scenarios 1 and 2. Although in Scenario 1 we used actual wind data for February extracted from the ECMWF reanalysis ERA5 model, in the second scenario, we utilized a constant wind speed of 4 m/s and a constant direction from the north-west. This is because the north-west wind predominates in this area throughout February and forces the oil to move in the southeast direction. The north-west wind regime accounts for about 24 % of the frequency of February in the northern part of the Gulf of Suez [56]. The current findings are consistent with Hussein [36], who used the GNOME oil spill model to simulate several anticipated oil spill scenarios under the influence of various wind regimes in the northern portion of the Gulf of Suez. She found that when the predominant wind is from the north-west direction, all oil spill trajectories flow in the southeast direction, toward the eastern shoreline of the Gulf. In this study, the spilled oil in both scenarios 1,2 reached the navigation lane of the Suez Canal within two to three hours. Also, approximately 30 to 38 kilometers of beaches south of the Suez Canal were threatened by oil contamination. Thus, in the case of an oil spill from a source at the southern entrance of the Suez Canal, the navigation lane via the Suez Canal and the area south of the Suez Canal would be the most vulnerable to contamination. This area has various crucial projects, such as the Ayoun Mousse power plant and several tourist resorts. Therefore, oil spill response personnel in the region must constantly be on alert.

In the case of the third scenario, the prevailing winds were from the north, the spill headed south, and almost three-quarters of all spilled oil continued to float in the water for 72 hours till the end of the simulation period. Therefore, the response teams could have enough time to choose the appropriate method to mitigate the effect of this spilled oil before it contaminates the coastline. Continuing with the fourth scenario, we assumed that the NE wind was dominant. In this scenario, the spilled oil moved southwesterly to the west coast of the Gulf of Suez. The movement direction of the oil in this scenario is consistent with Pradhan et al. [16], who simulated an oil spill in the Bay of Bengal, India. They observed that the oil moved in the southwest direction when northerly winds blew.

In this study, Scenario 4 represents a significant threat to the Green Island and the western coast of the Gulf of Suez, from Al-Adabiya port in the north to Ain Sukhna port in the south. This area is characterized by sensitive and fragile natural resources, habitats, vast coastal plain, extensive tidal flat, tourist resorts, and its aquatic environment hosting a vital coral reef [64].

The propagation of individual oil slicks over the water surface will be determined by the processes of turbulent diffusion [65]. The estimation of the radius of the diffusing impurity region according to [66] was determined by the ratio σ^2 [cm^2] = 0.0108$t^{2.34}$ (sec), where σ^2 is the average square of scattering of diffusing particles. A recent study [67] used trackers placed on sponge rubber pancakes. They compared the ratio of oil slick area between the simulation using the derived diffusion model and those using a constant value for the horizontal turbulent diffusion coefficient. They found that, there is no difference between the results simulated with the derived diffusion model and those obtained using a value of diffusion coefficient = 22 m^2/s, and their simulations agree well with the observed oil slick areas. GNOME used a constant diffusion coefficient ~10 m^2/s as model default. Therefore, it is necessary in future studies to carefully select the diffusion coefficient value.

To validate the results obtained from a spill model, remotely sensed data of a real case trajectory or a field experiment should be used. However, this final step cannot be achieved in this study owing to the lack of real cases and, more importantly, the lack of transparency about oil spills in the Egyptian waters, as the authorities are keen on promoting the tourism industry [36].

Weathering processes occur at varied speeds after the oil spill. Evaporation is the first weathering process that occurs after an oil spill. During this process, most volatile components of crude oil are removed within hours following the spill, which significantly impacts the density and viscosity of the oil slick [19]. As a result, determining the rate of evaporation is critical. ADIOS2 contains a pseudo-component evaporation model (Jones, 1997). In the pseudo-component approach, crude oils and refined products are modeled as a relatively small number of discrete, non-interacting components. Each pseudo component (PC) is treated as a single substance with an associated vapor pressure and relative mole fraction. The total evaporation rate of the slick is the sum of the individual rates [45]. The results show that approximately a quarter of the oil spilled was lost due to evaporation in all scenarios. The Arabian Light crude has a higher percentage of light and soluble fractions than other types of oil [37].

Emulsification is the process of incorporating water into the oil [19]. The negative impact of emulsification is an increase in the slick volume, which significantly raises the cleaning expense. Consequently, emulsification is a process that plays a significant role in oil spill modeling [1]. The results demonstrate that the emulsion water content was extremely high in all scenarios. It might be because the simulation period was in February, and the turbulence at the water's surface was at its peak. These results support the findings of Bozkurtoğlu [68], who suggested that turbulence at the sea surface promotes emulsion. the emulsification causes a rise in pollutant concentration. Therefore, these results about the behavior of oil after a spill are crucial for spill responders [10, 18].

The limitation of GNOME model is that it considers the oil slick a set of particles. There is a source of uncertainty because, for computational purposes, GNOME divide the slick into Lagrangian elements (LEs) or particles and tracks their movement, which doesn't calculate the oil spill area taking into account boundary conditions on the free and contact boundary, which the weathering processes directly depend on the area of the oil. Zatsepa et al. [69] created a new Eulerian-Lagrangian numerical method and developed SPILLMOD took into account the boundary condition. In ADIOS2, each LE, representing a changing volume of oil, constitutes the center of a Thiessen polygon with a surface area relative to the local density of LEs, allowing the estimation of a variable local thickness, based on the polygon area and oil volume. The approaches followed by Lagrangian oil spill models to compute oil surface area or thickness adds further uncertainty in the spreading estimation [1].

7. Conclusion

Since the Suez Canal is one of the world's busiest shipping routes, particularly for crude oil transit, it is vulnerable to oil spills, which may disrupt traffic, harm marine and coastal ecosystems, and threaten infrastructure and tourist resorts in the Gulf of Suez. This study simulates 1,000 metric tons of Arabian light crude oil that spilled into seawater on the 10th of February, 2021, at 12:00 am in the shipping lane about 2 km from the Suez Canal's southern entrance. Four scenarios were simulated using GNOME and ADIOS2 models in different wind conditions to define the potentially affected regions, determine when the oil would reach the coast, how much oil remains in the water, and calculate the weathering processes of the spilled oil (evaporation and emulsification). The study revealed that the spilled oil movement had been influenced by the direction of the wind in each scenario and the seawater current direction in the region. The spilled oil movement in scenario 1.2 was influenced by the north-west NW wind and drifted towards the eastern shoreline of the Gulf of Suez and reached the beach within two to three hours. As a result, the Suez Canal

navigation lane and approximately 30 to 38 km of beaches south of the Suez Canal, which have several projects and touristic resorts, were endangered by oil pollution. The north wind in Scenario 3 forced the spilled oil to move in the south direction, and the high proportion of the oil (73.8 %) remained floating until the end of the simulation and did not threaten the beaches. In Scenario 4, the spill moved in the southwest (SW) direction toward the western coast of the Gulf of Suez under the influence of north-east NE wind. The spilled oil reached Green Island within two hours, and after 72 h, roughly 60.3 % of oil particles covered a distance of 40 km south of Al-Adabiya port to Ain Sukhna port. According to the ADIOS2 results, in all scenarios, a considerable portion of the spilled oil, almost a quarter of the oil, evaporated, and more than two-thirds of the oil emulsified.

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