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Effective Detection of Potential Oil Pollution in the Egyptian Maritime Routes of the Mediterranean Sea Using SAR Data

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ABSTRACT

Oil spills pose a significant threat to marine ecosystems and coastal regions, necessitating effective monitoring and analysis for environmental management and response planning. In response, this study focused on the detection and characterization of oil spills along the North coast of Egypt, specifically in the vicinity of Port Said and the northern entrance of the Suez Canal, using data acquired from the Sentinel-1 satellite and employing advanced remote sensing techniques and spatial analysis tools including the SNAP toolbox to process and analyze the data. Analysis of the oil spills monitored by the Sentinel-1 satellite in the Mediterranean Sea during 2018 and 2019 indicates the presence of a few larger spills with a significant impact. In 2018, the minimum area of an oil spill event was 0.512 Km^2, and the maximum area was 96.729 Km^2; while in 2019, the minimum and maximum areas of the oil spills were 0.679 km^2 and 46.866 km^2, respectively. Spatial distribution analysis utilizing GIS software demonstrates that oil spill events are not confined to specific areas but occur along the entire coast of the study area. Clustering of events is observed around Port Said, with a higher concentration in the eastern Mediterranean Sea, likely attributed to increased ship transportation activity. Temporal analysis reveals that oil spill events occur throughout the year, displaying variations in frequency and size. The findings of this study would provide valuable insights for environmental assessment and the development of mitigation strategies to minimize the impact of oil spills in the study area.

INTRODUCTION

The North coast of Egypt, situated in the northeastern Mediterranean Sea, is an area of particular interest and concern in terms of oil spill occurrences. This region encompasses the northern entrance of the Suez Canal and the port of Port Said, which are vital for global trade as well as experiencing heavy maritime. Oil spills have become a significant environmental concern, posing serious threats to marine ecosystems, coastal communities and economic activities worldwide. These incidents result in ecological damage, harming marine life, and causing long-lasting environmental impacts. Effective monitoring, detection and analysis of oil spills are crucial for mitigating their adverse effects and implementing appropriate response measures.

The Suez Canal plays a crucial role in facilitating global trade, providing a direct route for vessels between the North Atlantic Ocean and the northern Indian Ocean; this strategic waterway has been recognized as an invasion corridor due to its extensive maritime traffic and potential environmental risks associated with shipping activities **(Galil, 2006)**. Monitoring and understanding the environmental challenges such as oil spills in this area are essential for protecting the marine ecosystem and ensuring the sustainability of this vital trade artery.

Remote sensing technologies, particularly satellite-based systems, have proven to be effective for oil spill detection and monitoring over large spatial scales. Satellites offer regular and wide-area coverage, enabling real-time or near-real-time detection of oil spills. Synthetic Aperture Radar (SAR) sensors, in particular, have demonstrated their utility in oil spill monitoring due to their all-weather imaging capabilities and sensitivity to oil slicks on the sea surface **(Fingas *et al.*, 2017)**.

Several studies have focused on detecting and monitoring oil spills in the Mediterranean waters of Egypt. **El-Magd *et al.* (2021)** and **Kostianoy *et al.* (2020)** utilized remote sensing techniques, particularly Sentinel-1 Synthetic Aperture Radar (SAR) data to detect and map oil spills along the Egyptian coast. They achieved high accuracy in their detection methods and discussed the challenges specific to the region. Similarly, **Ahmed *et al.* (2023)** developed a deep neural network (DNN) approach that specifically targeted the Egyptian coastal regions in the northern Mediterranean Sea for oil spill detection, using Sentinel-1 data.

In addition to detection, researchers have emphasized the importance of modeling and simulating potential impacts of oil spills in the eastern Mediterranean Sea. **Alves *et al.* (2016)** and **Zodiatis *et al.* (2018)** presented numerical modeling approaches for oil pollution in the region, highlighting the need for integrating multidisciplinary data and models. **Alves *et al.* (2015)** further investigated the modeling of oil spills in confined maritime basins, stressing the significance of early response and effective oil spill modeling to protect coastal communities and the environment. Furthermore, **Kostianoy and Lavrova (2022)** provided a comprehensive overview of various satellite sensors, data sources, and image processing techniques used for oil pollution monitoring in the Mediterranean waters of Egypt. **Hussein (2021)** assessed the vulnerability of environmentally sensitive coasts to large oil spills in the northern part of the Gulf of

Suez. While, **Al-Ruzouq *et al.* (2020)** conducted a comprehensive review on sensors, features and machine learning techniques for oil spill detection and monitoring.

However, despite the increasing application of remote sensing technologies for oil spill analysis, there is a paucity of research specifically focusing on the vulnerability of the North coast of Egypt to oil spills. Therefore, this study aimed to analyze oil spill events along the North coast of Egypt using satellite-based remote sensing data, with a specific emphasis on the region of Port Said and the north entrance of the Suez Canal. The analysis will include examining the occurrence, size, distribution, temporal patterns of oil spills in the study area, and relation to ship traffic, contributing to a better understanding of the dynamics and impacts of oil pollution in the region.

MATERIALS AND METHODS

Study area

The study area is located in the northeastern waters of Egypt at the Mediterranean Sea. The area of Port Said and the north entrance of the Suez Canal were specifically examined as shown in Fig. (1). The port of Port Said is considered one of the busiest seaports in the world, serving as a major gateway for trade in the region. The Suez Canal, on the other hand, provides a direct route for vessels between the North Atlantic Ocean and the northern Indian Ocean, making it an important navigation route between Europe and Asia. Given that around 12% of global trade passes through the Suez Canal, it is reasonable to assume that the high frequency of vessel traffic could contribute to oil spills and discharge in the study area.

Image processing

The present study employed available Sentinel-1A and 1B (SAR-C) data acquired during 2018 and 2019 to detect oil spills in the northern segment of the Suez Canal. The Sentinel-1A and 1B data were obtained from The Copernicus Open Access Hub at Level-1 IW ground range detected high resolution (GRDH), with a spatial resolution of 5 × 20 m and dual-polarization (VV + VH). Given that SAR based oil spills detection technique provided highly accurate results at the wind speed of 3 to 9m/ s **(Naz *et al.*, 2021)**, thus it is confirmed that the oil spills detection had wind speeds ranging from 2.91 to 6.88m/ s only. Processing of the Sentinel data was carried out using the SNAP toolbox.

To encompass the study area, a subset was created from the Sentinel data. The subset images were then subjected to processing using a single-product speckle filter (Lee filter) to eliminate any remaining speckle noise. Subsequently, the filtered images underwent terrain correction using SRTM 3sec. Radiometric calibration was applied to ensure accurate representation of backscatter in each pixel. For the purpose of oil spill detection and clustering, the Sentinel-1 SAR-C data were processed by employing a proper background window dimension and a pre-estimated threshold decibel (dB), based on the profile plot, to extract the dark patches corresponding to the oil spills in the SAR images. In addition to the Sentinel-1 (SAR-C) data, the acquired data were converted to GeoTiff format and processed using ArcGIS Pro to calculate area, extract X and Y data, build data base to temporal events analysis and map production.

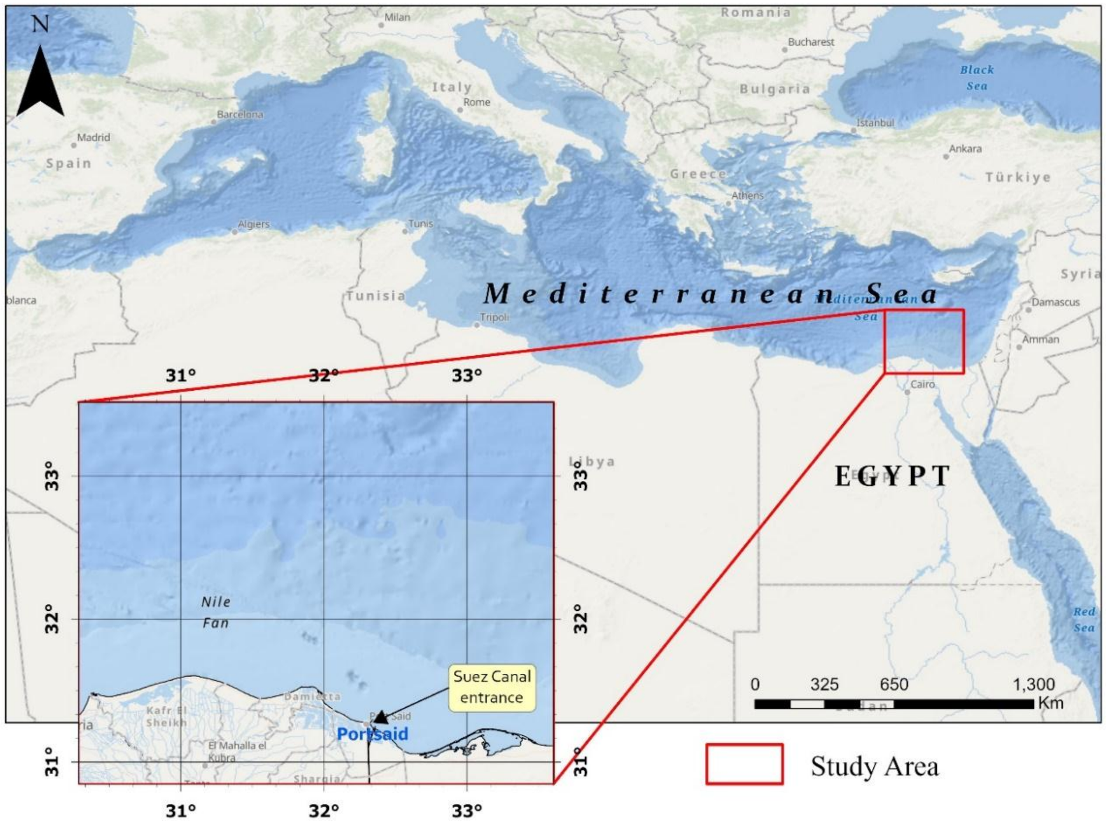

Fig. 1. A map of northern Egypt showing the study area

RESULTS AND DISCUSSION

1. Oil spill events in 2018

In 2018, a total of 23 oil spill events were effectively monitored in the Mediterranean Sea using the Sentinel-1 satellite. These events indicate the presence of a few larger spills that had a significant contribution to the overall distribution. The minimum area of an oil spill event was 0.512 Km^2 and the maximum area was 96.729 Km^2. Wind speeds recorded during these events ranged from 2.91 to 6.88 m/s, with an average of 4.36m/ s. The spatial distribution analysis revealed that the oil spill events were not confined to a specific area but occurred along the entire North coast of Egypt, with some clustering observed around Alexandria and Port Said. Our results in the number of accidents are close those of **El-Magd *et al.* (2021)** who investigated 19 incidents along the entire Egyptian region of the Mediterranean Sea. The concentration of events between latitudes 31° 16' N and 33° 18' N and longitudes 30° 32' E and 33° 18' E indicated a higher risk of oil spills in these regions, especially in the eastern Mediterranean Sea, where shipping activity was more prominent.

The spatial distribution analysis demonstrated that oil spill events were not confined to a specific area but occurred along the entire North coast of Egypt, with some clustering observed around Alexandria and Port Said, as shown in Fig. (2). This spatial pattern suggests that factors other than ship traffic alone may contribute to the occurrence of oil spills as demonstrated in Fig. (3). One possible contributing factor could be the presence of oil extraction and transportation infrastructure in the region. Research has shown that oil exploration and production activities increase the risk of oil spills in marine environments **(Michel and Fingas, 2016).** The concentration of oil spill events in the eastern Mediterranean Sea, where shipping activity is higher. **(Alves *et al.*, 2015).**

Furthermore, the analysis of navigation routes and ship traffic in the Suez Canal during 2018 revealed interesting patterns. Table (1) shows the occurrence and size of oil spills. Whereas, factors such as operational practices, adherence to safety protocols, and spill response capabilities might play a significant role in the occurrence and mitigation of oil spills. It is important to note that the Suez Canal is a major shipping route, and strict regulations and guidelines are in place to prevent and respond to oil spills (**Suez Canal Authority, 2021)**. However, occasional incidents may still occur due to human ethical behavior, mechanical failures or natural causes, which could explain the observed variations in oil spill events.

2. Oil spill events in 2019

In 2019, the Sentinel-1 satellite monitored 19 oil spill events along the North coast of Egypt, as shown in Fig. (4). These spills varied in size from 0.679 to 46.866 km^2, Similar to 2018, the distribution of spill sizes in 2019 indicates the predominance of relatively small spills, with a few larger spills impacting the overall distribution. Wind speeds during these events ranged from 2.71 to 6.23m/ s, as demonstrated in Table (2). The temporal analysis revealed that oil spill events occurred throughout the year, with varying frequencies and sizes. Our results in the number of accidents coincide with those of **El-Magd *et al.* (2021)** who found 30incidents on the entire Egyptian region of the Mediterranean Sea, while our results differ with those of **Abou Samra *et al.* (2022)** who surveyed the same study area, while the number of accidents was small (11 incidents); this was due to using Sentinel 2 data and a different method (parallelepiped classification) in their study.

The spatial distribution analysis showed that the oil spills were distributed along the North coast of Egypt within the specified latitude and longitude range, as shown in Fig.

(5). The GIS analysis using ArcGIS software visualized and assessed the distribution of these events effectively, providing valuable insights into the extent and patterns of oil pollution in the area.

The spatial distribution analysis showed that the oil spills were distributed along the North coast of Egypt within the specified latitude and longitude range. This spatial pattern confirms the findings from 2018 and suggests that multiple factors contributed to the occurrence of oil spills in this region. Apart from shipping activity, other potential factors include the presence of oil terminals, refineries and industrial activities along the coast. Industrial discharges and accidental releases from these facilities can contribute to oil pollution in the marine environment **(Ivshina *et al.*, 2015)**. Moreover, improper waste management practices including the discharge of oily waste from vessels can also contribute to localized oil spill events (**Dave & Ghaly, 2011)**.

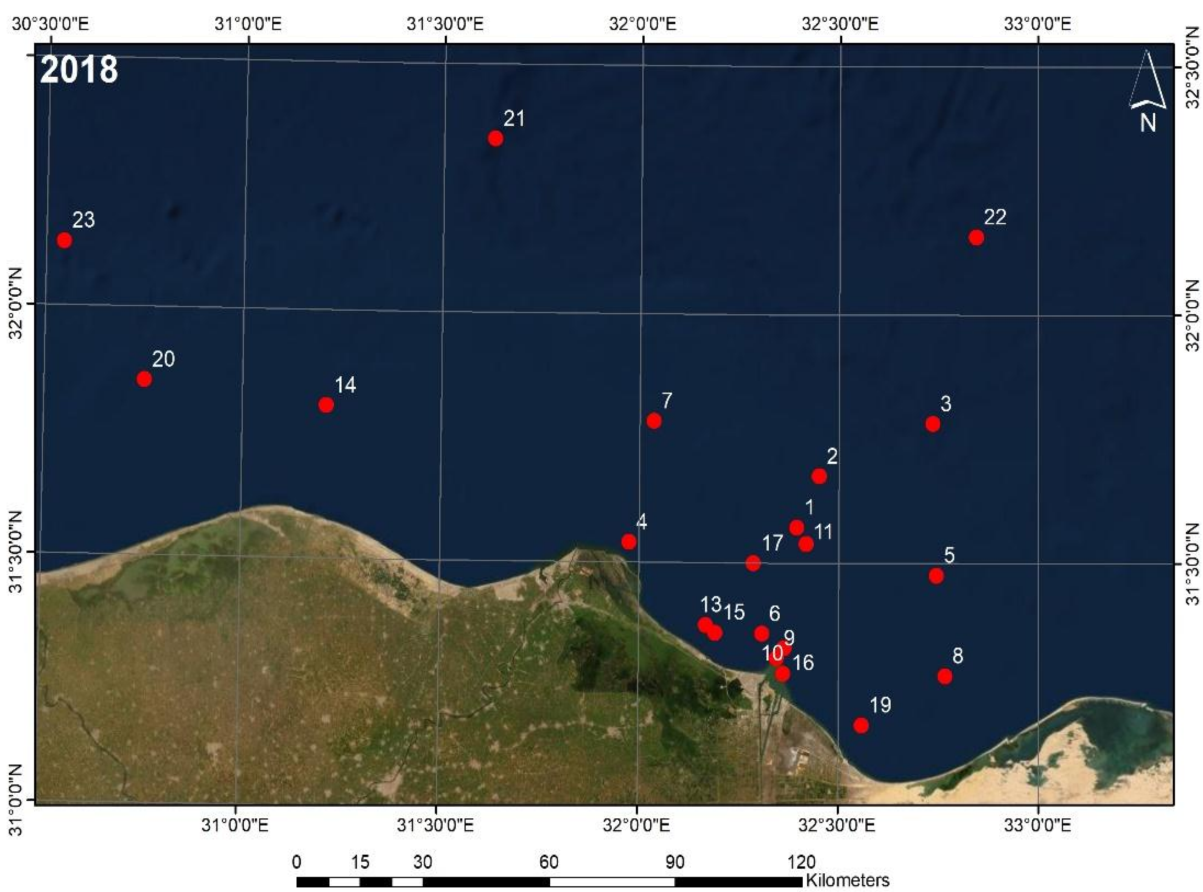

Fig. 2. Geographic location points ID of oil spill incidents in 2018

Table 1. Oil spill events in 2018 with its accurate spatiotemporal data

Point	Date	Area (km^2)	Sentinel Type	Y-coordinates (dms)	X-coordinates (dms)	Wind (m/s)	Flight direction
1	4/16/2018	0.815	S1B	31° 34' 19.344" N	32° 23' 41.763" E	4.72	ASCENDING
2	3/23/2018	1.478	S1B	31° 40' 31.047" N	32° 27' 3.822" E	6.88	ASCENDING
3	8/15/2018	12.189	S1B	31° 46' 53.309" N	32° 44' 11.176" E	5.42	DESCENDING
4	12/24/2018	2.364	S1B	31° 32' 25.927" N	31° 58' 28.348" E	3.38	ASCENDING
5	7/15/2018	36.538	S1A	31° 28' 33.701" N	32° 44' 42.906" E	4.52	ASCENDING
6	5/22/2018	4.314	S1B	31° 21' 27.109" N	32° 18' 32.305" E	2.96	ASCENDING
7	6/15/2018	15.892	S1B	31° 47' 4.235" N	32° 2' 8.299" E	3.9	ASCENDING
8	10/19/2018	3.630	S1A	31° 16' 25.443" N	32° 46' 2.160" E	3.34	ASCENDING
9	5/11/2018	4.058	S1B	31° 18' 29.334" N	32° 20' 43.647" E	3.57	DESCENDING
10	11/18/2018	2.451	S1B	31° 16' 38.859" N	32° 21' 43.183" E	4.26	ASCENDING
11	7/3/2018	20.963	S1A	31° 32' 19.887" N	32° 25' 8.204" E	3.2	ASCENDING
12	2/10/2018	89.487	S1A	33° 18' 38.506" N	33° 18' 44.886" E	2.91	DESCENDING
13	3/18/2018	0.512	S1A	31° 22' 27.759" N	32° 10' 3.657" E	5.8	DESCENDING
14	2/28/2018	31.515	S1B	31° 48' 27.633" N	31° 12' 39.454" E	3.24	DESCENDING
15	1/10/2018	13.814	S1B	31° 21' 32.564" N	32° 11' 28.208" E	6.11	ASCENDING
16	3/17/2018	2.184	S1A	31° 19' 43.949" N	32° 21' 52.577" E	5.41	ASCENDING
17	1/28/2018	13.842	S1A	31° 29' 57.741" N	32° 17' 13.064" E	4.43	ASCENDING
18	11/6/2018	31.834	S1B	32° 44' 6.175" N	31° 44' 28.962" E	4.27	ASCENDING
19	1/17/2018	1.847	S1A	31° 10' 26.177" N	32° 33' 31.473" E	3.52	DESCENDING
20	12/24/2018	75.695	S1A	31° 51' 9.247" N	30° 45' 12.848" E	5.59	DESCENDING
21	3/5/2018	96.729	S1A	32° 20' 58.852" N	31° 37' 45.911" E	3.44	ASCENDING
22	3/17/2018	56.290	S1A	32° 9' 27.829" N	32° 50' 41.524" E	4.17	ASCENDING
23	3/23/2018	2.229	S1A	32° 7' 43.876" N	30° 32' 43.318" E	6.53	DESCENDING

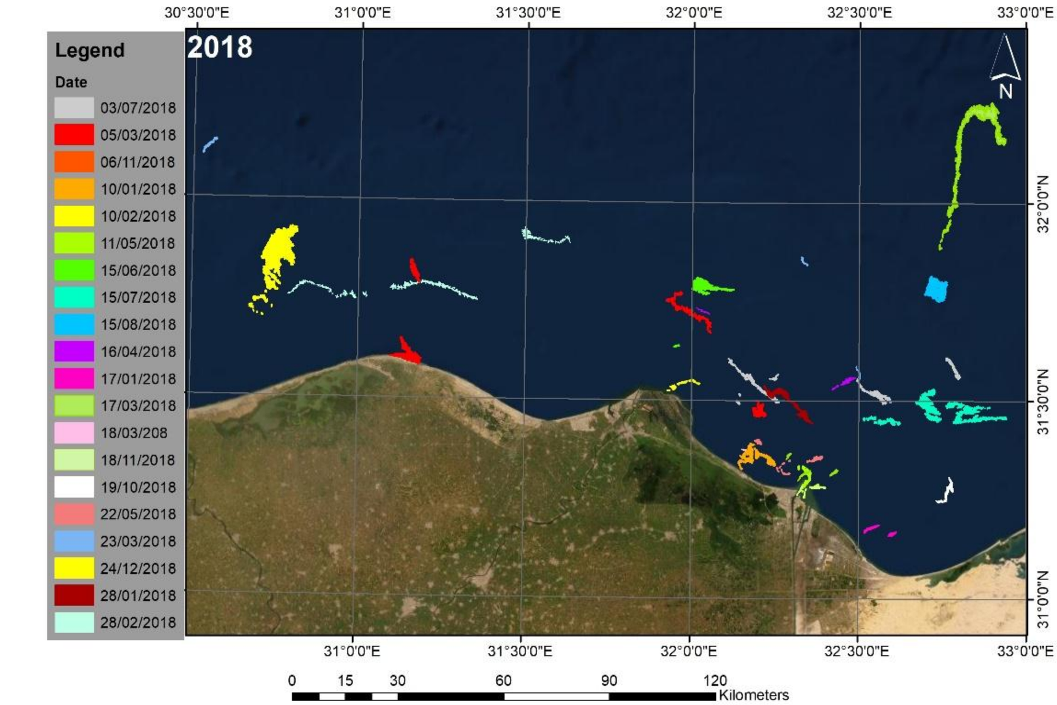

Fig. 3. Accumulated map of oil spills shapes detected by SAR images in 2018 with dates

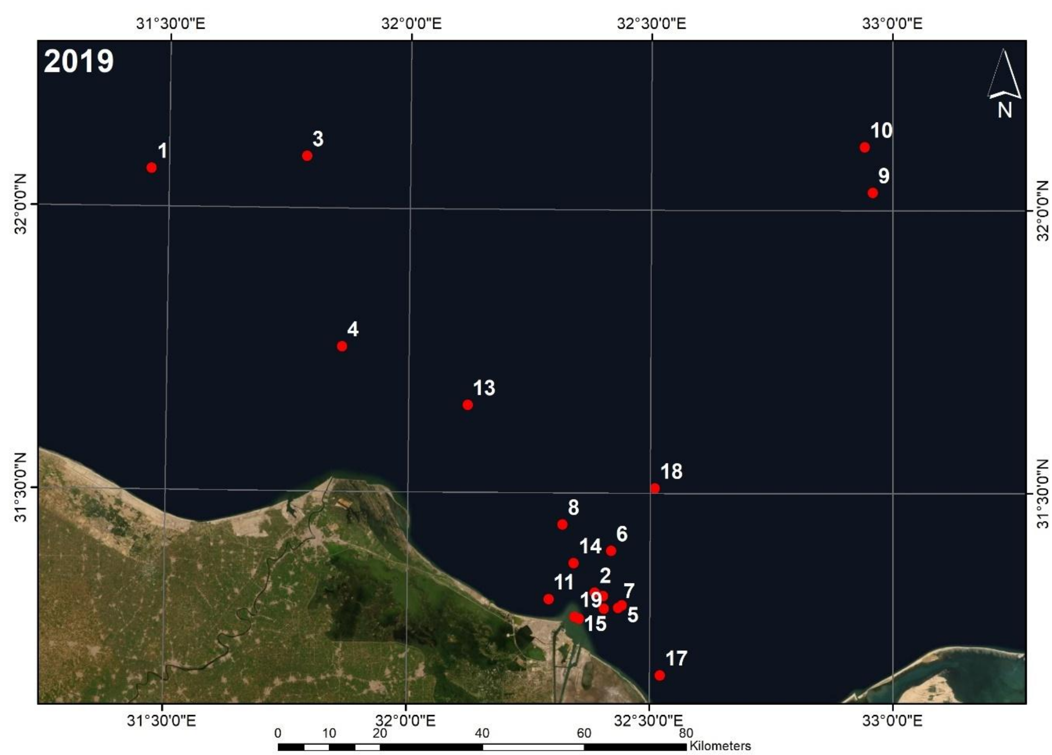

Fig. 4. Geographic location points ID of oil spill incidents in 2019

Table 2. Oil spill events in 201 9with its accurate spatiotemporal data

Point	Date	Area (km^2)	Sentinel type	Y- coordinates (dms)	X- coordinates (dms)	Wind (m/s)	Flight direction
1	5/12/2019	15.379	S1A	32° 4' 0.344" N	31° 27' 48.914" E	5.14	DESCENDING
2	4/11/2019	2.283	S1B	31° 19' 25.278" N	32° 23' 12.491" E	5.41	ASCENDING
3	8/27/2019	14.789	S1A	32° 5' 27.760" N	31° 47' 7.397" E	4.57	ASCENDING
4	4/29/2019	0.847	S1A	31° 45' 19.952" N	31° 51' 42.536" E	2.93	ASCENDING
5	8/10/2019	7.348	S1B	31° 18' 5.890" N	32° 26' 34.114" E	4.8	DESCENDING
6	2/23/2019	22.771	S1B	31° 23' 52.940" N	32° 25' 12.434" E	2.71	DESCENDING
7	12/7/2019	4.944	S1B	31° 17' 48.025" N	32° 26' 7.704" E	4.03	ASCENDING
8	8/22/2019	23.383	S1B	31° 26' 39.383" N	32° 19' 12.558" E	6.23	DESCENDING
9	4/6/2019	20.038	S1A	32° 1' 53.647" N	32° 57' 33.376" E	4.93	DESCENDING
10	9/21/2019	6.620	S1A	32° 6' 41.994" N	32° 56' 31.911" E	5.14	DESCENDING
11	4/5/2019	4.808	S1A	31° 18' 41.752" N	32° 17' 34.009" E	3.3	ASCENDING
12	8/21/2019	7.756	S1B	31° 17' 44.379" N	32° 24' 21.683" E	4.25	ASCENDING
13	8/4/2019	15.729	S1A	31° 39' 14.480" N	32° 7' 21.003" E	4.56	DESCENDING
14	10/20/2019	0.859	S1B	31° 22' 32.589" N	32° 20' 36.127" E	4.17	ASCENDING
15	7/4/2019	0.679	S1B	31° 16' 39.433" N	32° 21' 16.438" E	4.73	ASCENDING
16	12/19/2019	46.866	S1B	31° 19' 3.909" N	32° 24' 16.684" E	4.61	ASCENDING
17	10/2/2019	8.980	S1A	31° 10' 41.679" N	32° 31' 17.107" E	5.25	ASCENDING
18	3/18/2019	14.260	S1B	31° 30' 31.218" N	32° 30' 34.513" E	3.92	ASCENDING
19	4/29/2019	1.717	S1A	31° 16' 50.475" N	32° 20' 42.805" E	3.85	ASCENDING

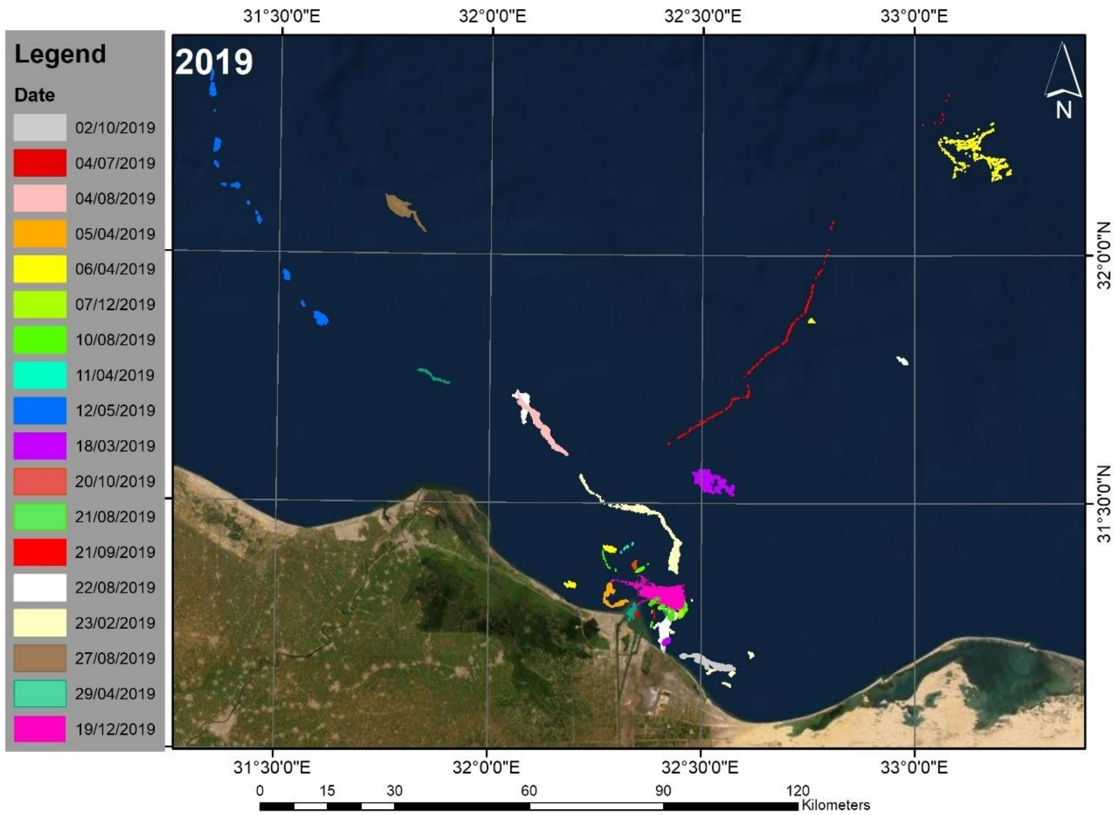

Fig. 5. Accumulated map of oil spills shapes detected by SAR images in 201 9with dates

3. Navigation routes and event occurrence

The spatial analysis of oil spill events along the North coast of Egypt from 2018 to 2019 highlighted the relation between navigation routes and the occurrence of these events. The concentration of oil spills in the eastern Mediterranean Sea suggested a higher occurrence of events in areas with increased shipping activity (Fig. 6). To further explore this relationship, Fig. (7) displays information on the month of oil spill events, their corresponding numbers, and the number of ships passing through the Suez Canal during each month from January 2018 to December 2019.

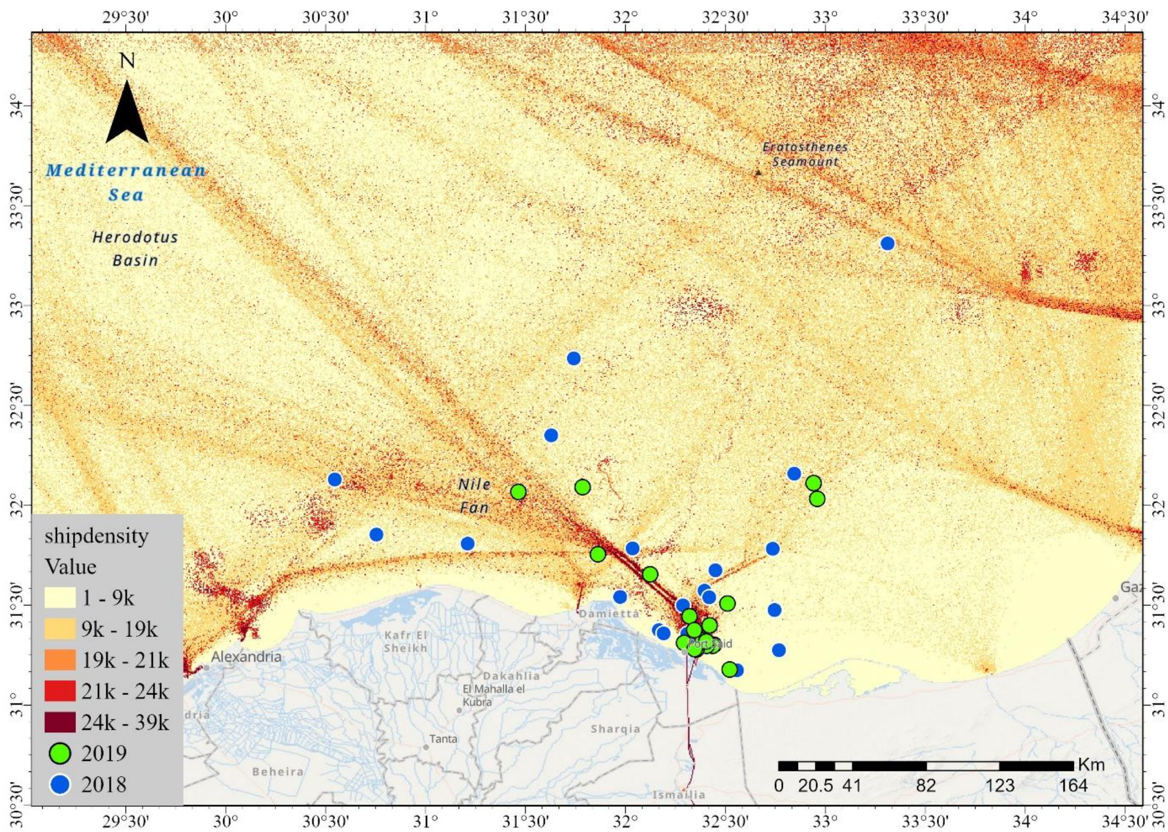

Fig. 6. A map showing the location of oil spill events with respect to ship density

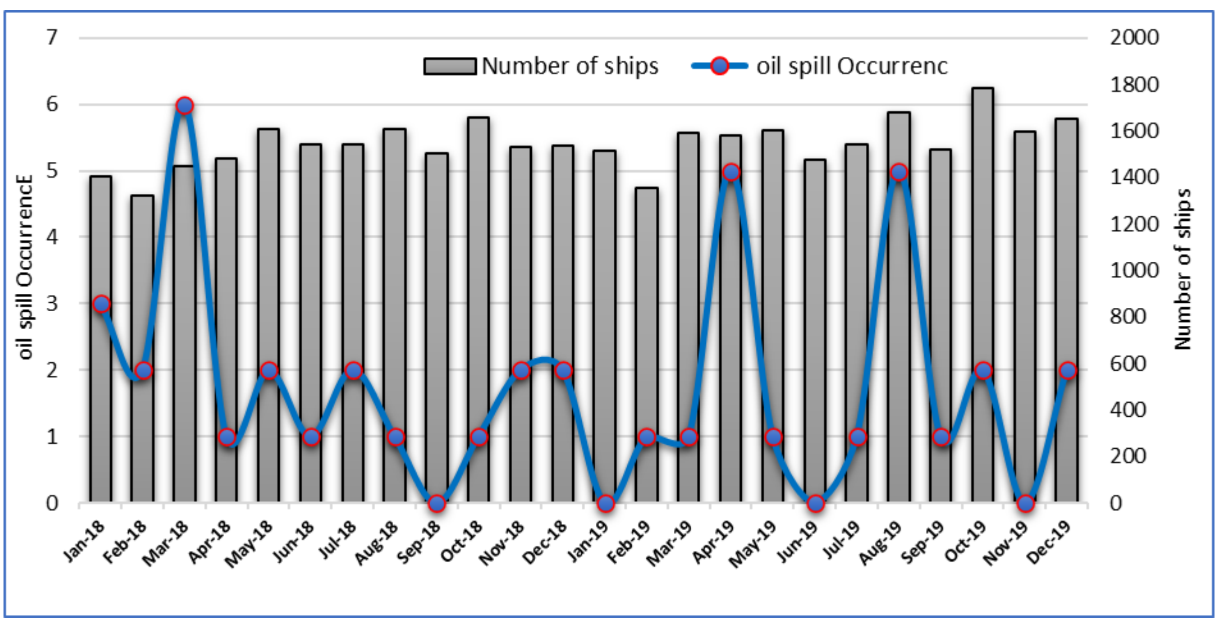

Fig. 7. A histogram showing the relation between ship numbers and oil spill occurrence

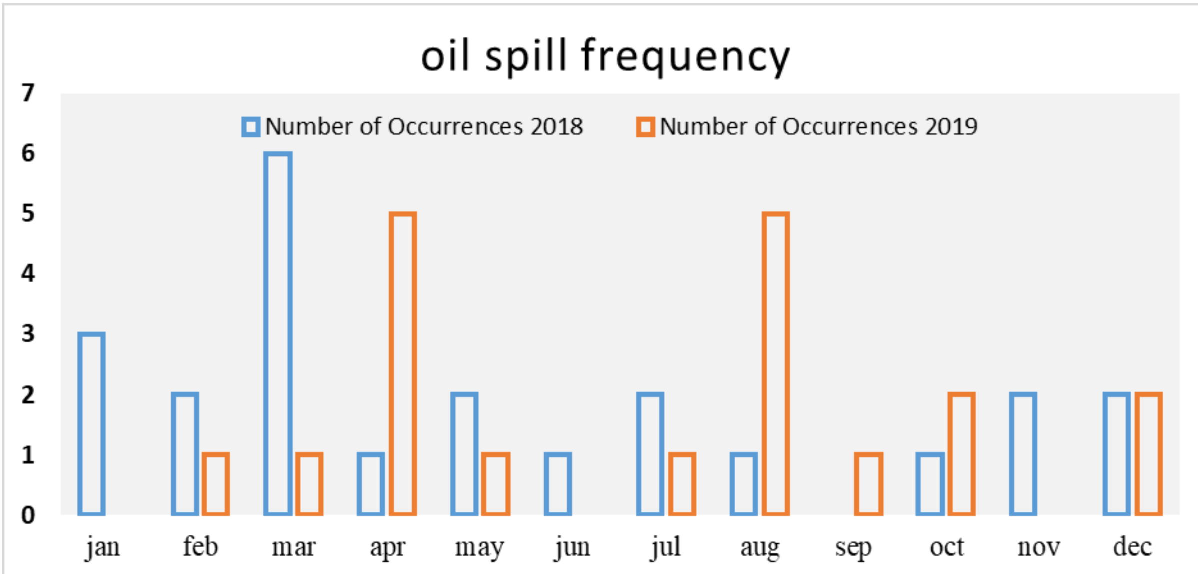

Fig. 8. Oil spill frequency by months for 2018 and 2019

The analysis of data revealed variations in the frequency of oil spill events throughout the months, indicating that the occurrence of oil spills is not consistent and can vary significantly, as shown in Fig. (8). The total area of all recorded oil spill events during the analyzed period was 740.73 km^2, highlighting the extent of environmental impact caused by these spills. Interestingly, the number of ships passing through the Suez Canal did not have a direct correlation with the occurrence or size of oil spills, suggesting that other factors contribute to the occurrence and size of these events in the study area.

One significant factor is the vulnerability of the marine ecosystem in the region. The North coast of Egypt is characterized by sensitive ecosystems,; thus, any oil spill in this area can have severe ecological and economic consequences **(Islam & Tanaka, 2004)**. Additionally, the presence of shallow waters and intricate coastal geography can exacerbate the impacts of oil pollution, leading to increased harm to marine ecosystems and coastal communities **(Beyer *et al*., 2016)**.

Another factor to consider is the enforcement of regulations and compliance with international standards regarding vessel operations and safety measures. Despite the existence of international conventions and guidelines to prevent oil pollution from ships, compliance can vary among different vessels and operators. The effectiveness of port state control and the implementation of inspection regimes can play a crucial role in mitigating oil spill incidents.

CONCLUSION

The analysis of oil spill events in the Mediterranean Sea along the North coast of Egypt during 2018 and 2019 has provided valuable insights into the characteristics and distribution of these incidents. The findings reveal that oil spills in the region are not solely influenced by ship traffic volume but are also affected by various other factors. The spatial distribution analysis demonstrated that oil spills occurred along the entire North coast of Egypt, with some clustering observed around Alexandria and Port Said. This suggests that factors such as the presence of oil extraction and transportation infrastructure, vulnerability of the marine ecosystem and industrial activities along the coast contribute to the occurrence of oil spills. The relationship between navigation routes and the occurrence of oil spill events is complex. While the concentration of events in the eastern Mediterranean Sea suggests a higher occurrence in areas with increased shipping activity, the analysis revealed that the number of ships passing through the Suez Canal did not directly correlate with the occurrence or size of oil spills. Consequently, factors such as ship operational practices, adherence to safety protocols, spill response capabilities and the enforcement of regulations all contribute significantly to the occurrence of oil pollution.

Recommendation

To mitigate the occurrence of oil spills and their impacts, a multi-faceted approach is required. This approach should include regular monitoring and surveillance using satellite technology, especially around navigational routes, strengthening regulations and enforcement mechanisms, enhancing spill response capabilities, promoting environmentally sound practices in maritime operations, and raising awareness among authorities about the importance of marine environmental protection.

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