


Article

The Potentiality of Operational Mapping of Oil Pollution in the Mediterranean Sea near the Entrance of the Suez Canal Using Sentinel-1 SAR Data

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Abstract: The Suez Canal, being a main international maritime shipping route, experiences heavy ship traffic with probable illegal oil discharges. Oil pollution is harming the marine ecosystem and creates pressure on the coastal socio-economic activities particularly at Port Said city (the area of study). It is anticipated that the damage of oil spills is not only during the event but it extends for a long time and normally requires more effort to remediate and recover the environment. Hence, early detection and volume estimation of these spills is the first and most important step for a successful clean-up operation. This study is the first to use Sentinel-1 space-borne Synthetic Aperture Radar (SAR) images for oil spill detection and mapping over the north entrance of the Suez Canal aiming to enable operational monitoring. SAR sensors are able to capture images day and night and are not affected by weather conditions. In addition, they have a wide swath that covers large geographical areas for possible oil spills. The present study examines a large amount of data (800 scenes of sentinel 1) for the study area over a period of five years from 2014 till 2019 which resulted in the detection of more than 20 events of oil pollution. The detection model is based on the quantitative analysis of the dark spot of the radar backscatter of oil spills. The largest case covered nearly 26 km² of seawater. The spill drift direction in the area of spills indicated potential hazard on fishing activities, Port Said beaches and ports. This study can be the base for continuously monitoring and alarming pollution cases in the Canal area which is important for environmental agencies, decision-makers, and beneficiaries for coastal and marine socio-economic sustainability.

Keywords: Synthetic Aperture Radar (SAR) data; oil spills; image processing techniques; Suez Canal; Mediterranean Sea

1. Introduction

Oil pollution is frequently seen in the marine environment and is mainly related to the main shipping routes [1]. An amount of about 457,000 tons of oil has been estimated to be released into the ocean yearly only by navigation ships [2]. Statistically, of the observed oil pollution in the oceans, discharged fuels represent 48% while crude oils represent 29%; and only 5% comes from tanker accidents annually [3].

Oil spill pollution is considered a developmental constraint and socio-economic problem as it affects the marine ecosystem, economy, and human food chain [4]. The toxic compounds contained in

oil causes huge damage to sea-life and persist for a long period of time [5]. It is reported that impacts of oil pollution can last for decades and even small spills can spread over a very large aerial coverage.

Deliberate oil spills in the form of controlled discharges from ships form more a major threat than large oil accidents. Most of them are small in size and quickly disappear in a few hours and the thickness decreases that could not be observed by regulating authorities. These spills are hazardous to all the marine creatures and beaches contaminated by them and it is crucial to be delineated [4]. In the case of a C-band SAR, the oil layer must be thicker than 1 mm and in the case of the L-band SAR, thicker than 4 mm with aerial coverage not less than 100 square meters [4,5].

Compared with optical sensors, radar sensors are preferred for sea pollution monitoring. Working within the microwave range, the image is not affected by clouds and different weather conditions. More importantly, it works day and night which gives the chance not to miss recording any of oil spills occurring at night. Moreover, it provides a wide range of spatial coverage at a low cost compared to airborne surveillance [6].

Synthetic Aperture Radar (SAR) uses a microwave beam to form a two-dimensional image of the backscattered wave from the ocean and uses the doppler history to synthesize high resolution in the along-track direction. The signal contains information about the level of roughness of the sea surface which is mainly driven by the wind. So, generally, the backscatter increases with the wind speed. The SAR beam interacts with the physical surface of the water, so it can detect waves, ships, oil spills or any physical object different from the water surface [7]. Dual-polarized (VV and HH) C - band SAR combination is the most efficient for that purpose but without the capability to estimate slick thickness or identify oil type [8].

However, aircraft can identify the polluter and spill type [2]. Infrared sensors can quantify the oil layer extent as it causes absorption at specific wavelengths 0.8, 1.2, 1.73, and 2.3 μm and thermal infrared can detect the slick based on the temperature anomaly between the oil spill and the surrounding water [9–11]. SAR had been used in the Deepwater Horizon oil spill monitoring [12]. The microwave radiometer (MWR) can determine the spill thickness and Laser-fluoro-sensor (LFS) can classify the spilled oil type [2]. Moreover, hyperspectral images can be employed as an auxiliary verification method for day time observations [11].

Oil spill dynamicity in the media over time is largely dependent on various processes such as; spreading, evaporation, emulsification, and dispersion, which mainly control the physical and chemical properties of any oil slicks. These processes are mainly dependent on oil type, oil thickness, sea and wind state. Oil natural dispersion rate at moderate wind is about 0.5–2% of the oil volume/hour [12]. Typical physical transport of 1 ton of oil after only ten minutes of the spill can cover a radius of 50 m with a slick thickness of 10 mm. That slick can continue spreading till covering an area of about 12 km^2 and thickness of less than 1 mm. When the slick thins to 0.1 mm, it disintegrates into small fragments covering larger areas and reaching further distances [13]. Spill thickness is not detectable by SAR images but it could be estimated based on visual approximations and past experience. The average thickness of an oil spill appearing in a SAR image is at least 1 μm [14]. Therefore, satellites of wider swath coverage and faster repeat cycles such as Sentinel 1 are better to detect such a dispersion process.

The Suez Canal usually has dense traffic as an important international navigation canal connecting the Red Sea and the Mediterranean Sea. Due to its distinct geographic location; it is considered the shortest path between the east and the west for maritime shipping and goods transportation particularly the transport of crude oil from the Arab region to Europe and the USA [15]. The canal is crossed by nearly 20,000 vessels annually including 2500 tankers with the probability of oil discharges in the marine environment [16]. These oil spills can harm the near economic area of Port Said city regarding fishing and tourism activities, and even coastal ecosystems and resources can be badly affected. However, there has been some research done on the eastern Mediterranean [17]; few research studies have been done on the Egyptian coastal area and there is an urgent need for near-real-time detection of any oil spill events [18]. This study aims at mapping oil spill events that occurred in the target area during the past five years using SAR technology and providing a robust model to detect

such pollution events in the future. It is also aiming at exploring the probable direct impact of the spills on the near coastal area and the proposed hazards over the area of study.

2. Area of Study

The Suez Canal is a big international navigation canal connecting the Red Sea and the Mediterranean Sea. Due to its distinct geographic location; it is considered the shortest path between the east and the west for maritime shipping and goods transportation particularly the transport of crude oil from the Arab region to Europe and the USA [15].

The north entrance of the Canal at the Mediterranean Sea between longitudes $32^{\circ}7'13''\text{E}$ and $32^{\circ}39'18''\text{E}$, latitudes $31^{\circ}40'14''\text{N}$ and $31^{\circ}9'57''\text{N}$ was chosen to be the area of study as shown in Figure 1. Due to the heavy load of shipping movement, there is a high probability of oil slicks. The study area covers nearly 50 km wide and 56 km long of seawater.

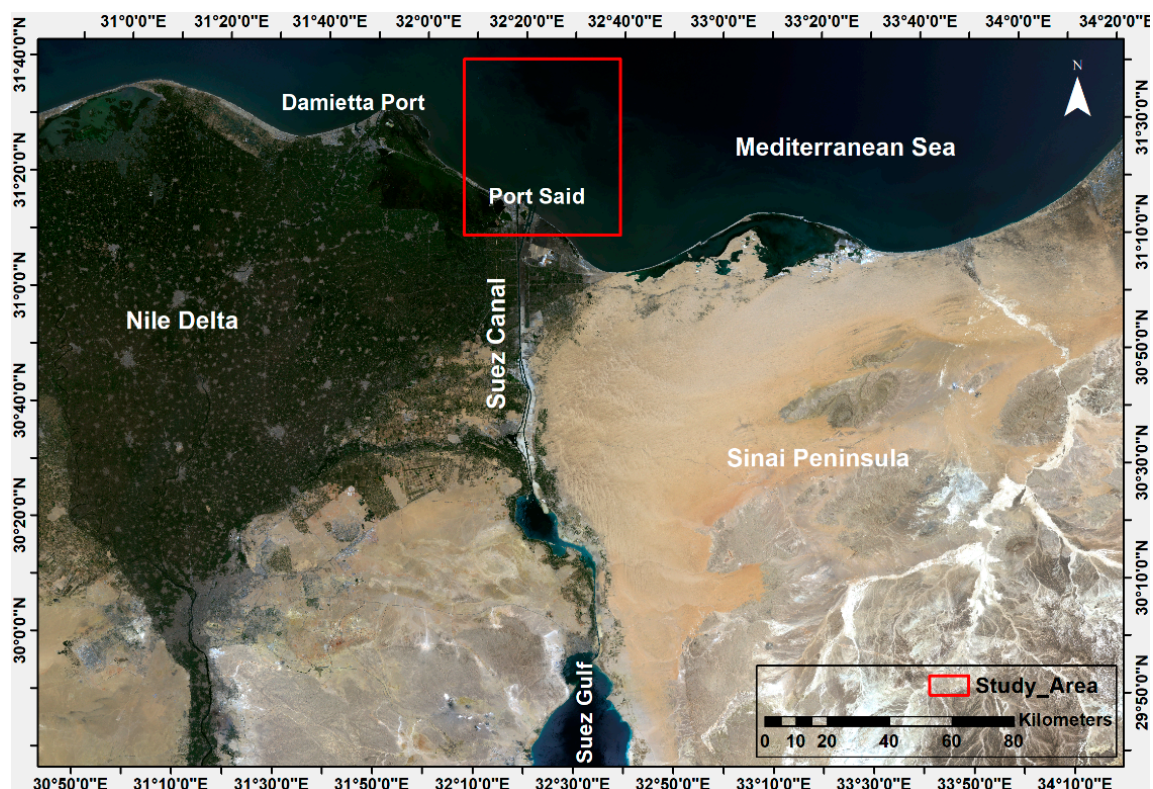


Figure 1. The area of study.

It is recorded that the averaged wind speed is (3 to 7 m/s) at the study area which enables the detection of oil spills using SAR data during the whole year's ranges. The current drift direction near Port Said city is southwest as shown in Figure 2 [19].

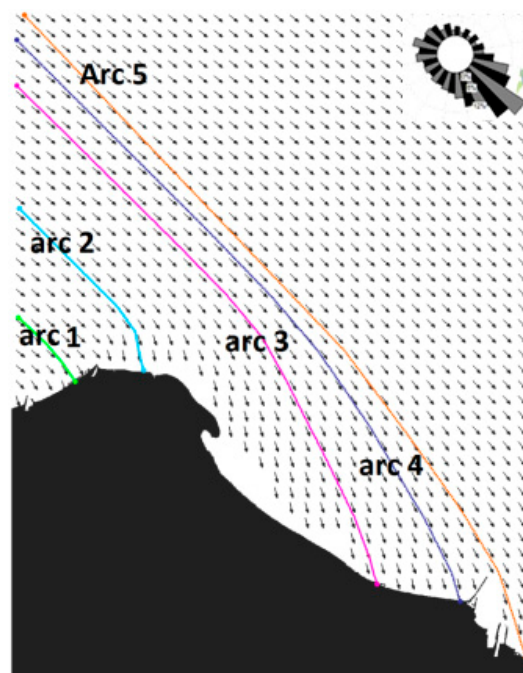


Figure 2. Average wave direction off Damietta Port Said coast, these five arcs from 1 to 5 are perpendicular to the wave crest and ordered southwards to simulate the changes in wave height moving from deep water towards the land. They range is between 1.56 and 2.06 for the study area.

3. Materials and Methods

3.1. Data Sources

Sentinel 1 SAR images are obtained freely from the European Space Agency (ESA) under the open data access policy by ESA. ESA Sentinel Data Hub is an online data browser that enabled us to explore the available satellite scenes, online visualization, and inspection prior to the actual download for processing. This online browser is efficient and saves time for processing unnecessary data [20].

Table 1 illustrates the technical specifications of the SAR Sentinel 1 images used in this research. SAR sensors have technical competency of capturing images with some unique technical elements such as polarisation that sustain the geometry of the tip of the electric vector, the incidence angle that sustains the angular relationship between the radar beam and the ground target, and the image resolution which reflects the size of the smallest detail identifiable on an image.

Table 1. Data Source Technical Specifications.

Item	Specs
Satellite (sensor)	Sentinel-1A, 1B
Band	C
Polarization	VV
Wavelength	5.5 cm
Acquisition Mode	Interferometric Wide Swath (IW)
Product Type	Ground Range Detected (GRD)
Resolution(m)	5 × 20
Swath Width (km)	250
Incidence Angle (°)	29.1–46
Repeat Frequency	2–6 days

3.2. Theoretical Background

Water waves are induced by wind and balanced by sea surface tension forming main gravity waves and secondary capillary waves. The short gravity-capillary waves—called Bragg waves—reflect radar radiation forming a bright area in the image called sea clutter. Oil is a viscous material and where there is an oil film on the water surface, Bragg waves are dampened. This reduces the backscattered radar energy, which forms dark pixels in SAR images. Figure 2 above shows these waves on a normal water surface [21]. Any anomaly of darker formation than the surrounded area in a SAR image will be an indication of a probable oil spill pollution and requires more investigation to characterize whether it is an oil spill or any other look-alike object.

3.3. Method

There are three approaches for processing the raw data for oil spill detection purposes; the fully automated, semi-automated, and manual approaches. Oil spill detection in the marine environment is a complicated task to be fully automated and needs human intervention in the detection process [22]. The manual approach is the most commonly used and carried out by experienced operators trained to explore SAR images for detecting probable oil spills [23]. Unfortunately, this approach is time-consuming and the confidence level is based on the interpreter and his personnel experience. The semi-automated and fully automated approaches incorporate expert knowledge into an automatic algorithm to save time [24]. These approaches are complex and under-developed since they require many training data sets to the classifier. It is a cost-effective method in monitoring large sea areas compared to the manual approach. Therefore, in this research, a semi-automated approach is adopted and methodology is developed to achieve this approach.

Raw data are processed to map probable oil spills according to the model framework illustrated in Figure 3 in a manual approach using the Sentinel Application Platform (SNAP) software toolbox. The model extracts the dark spots which may be oil spill events based on the contrast difference in the image using a pre-determined threshold.

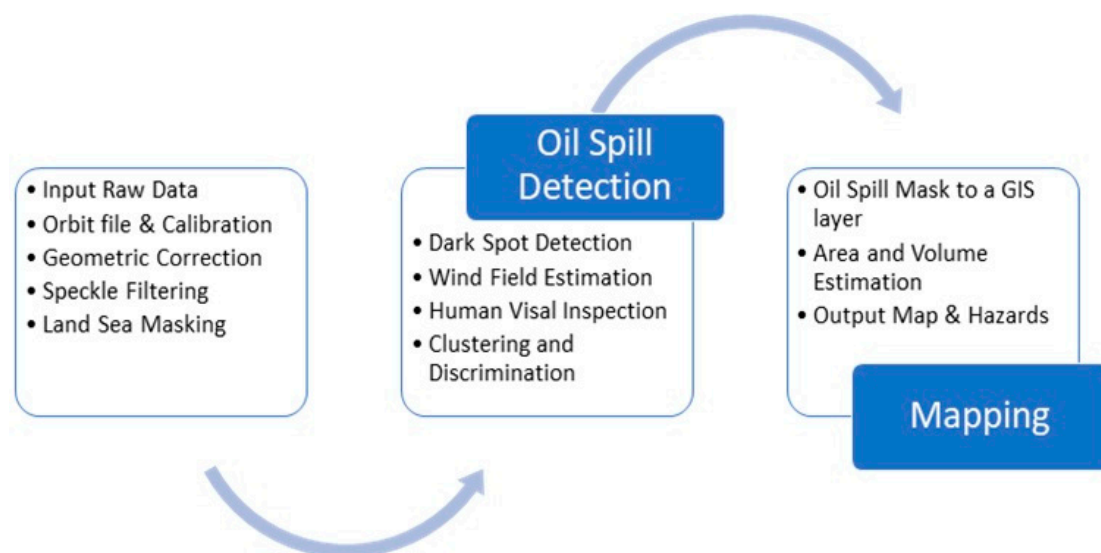


Figure 3. A schematic logical model framework of data processing.

The model shows three different but sequential data processing stages:

1. The raw images are preprocessed in multiple steps. First, improving the location accuracy of the images using the orbit file. Second, SAR calibration made to make sure that each pixel value actually represent the radar backscatter of the scene and that is important for the quantitative use

- of data. Then, data trimmed to the target area followed by Lee speckle filtering. Last, land-sea masking to make sure that the only available pixels for processing are the water pixels.
2. The SAR images are processed for oil spill clustering. It is done using a dynamic window of x pixels scanning the image and looking for dark areas according to a pre-defined threshold and here it is set to be from 2.5 to 4 dB. The wind vector can be estimated from the radar backscatter in the image as when the wind blows across the ocean surface, it creates surface roughness related to the wind speed and direction. At some stages, human experience is necessary to differentiate between whether the dark spot is an oil slick or look-alike based on the spot pattern, wind field calculation, and area ancillary data.
 3. Finally, the clustered oil mask is converted to a GIS layer for further spatial analysis such as area calculations, volume estimation, hazard prediction, and other mapping requirements.

3.4. SAR Limitations

Although the SAR image is not affected by weather conditions, the wind speed affects the backscatter and detectability of slicks on the water surface as shown in Figure 5. For wind speeds less than 3 m/s, it is difficult to distinguish between a clean sea surface and an oil spill. The wind will have no impact and a calm sea surface causes a specular reflection of radar waves far from the antenna. Additionally, wind higher than 10 m/s will disperse the spill into thinner and small fragments which makes it invisible and also the spill surface will have diffuse scattering. A moderate range from 3–10 m/s is the most suitable for the detection process [2]. Wind speed can be estimated from the SAR image itself by applying the CMOD4 model [21]. Summer from April to September is the most suitable season for such wind speed range.

Additionally, the SAR image may contain natural dark patches not resulted from an oil spill called look-alikes. Other natural phenomena like natural films secreted by fish, algal blooms, rain cells, ship wakes, internal waves, etc. can cause these dark patches [22]. The study is only interested in man-made slicks of petroleum products.

One of the main limitations is the discrimination of oil spill from the look-alike, which is difficult and requires experience and/or an intelligent algorithm. The author's improved the precision of such discrimination based on literature reviews and observation of well-documented oil spill cases [2]. The idea is many look-alike features can give the same backscatter as an oil spill, but there are many other features that could solely discriminate the oil spill; such as (1) geometric pattern, (2) marine infrastructure that could be strong evidence to be correlated with an oil spill. For example, a longitudinal dark spot with a bright spot at the end means a ship discharging oil in its pathway.

Speckles are a kind of noise related to SAR images, which appear as a salt and pepper texture in the image resulting from the individual interference between radar backscattered beams within the resolution cell. Lee demonstrated a model for treating speckles and it proved to be reliable for oil spill applications [23].

One last difficulty with SAR images is the large revisit time. It is an obstacle in continuous monitoring for oil spills which disappears very fast. As the orbit track spacing of the satellite varies with latitude and due to the location of the study area, the revisit time for that study is from 1–3 days.

4. Results

During the period of five years (2014–2019), more than 600 scenes of Sentinel 1 images have been explored online using the Sentinel data hub browser. This online exploration has initially checked visually the Sentinel data for the presence of dark spots. The outcomes of the initial visual exploration identified nearly 70 scenes highly suspected for probable oil spills. Further, processing and model application has resulted in 20 oil spill cases with various sizes and aerial coverage. The identified oil spill cases are almost a few kilometers from the entrance of the Suez Canal. The largest event was observed on the 4th of October 2014 and covered nearly 26 km² (Figure 4).

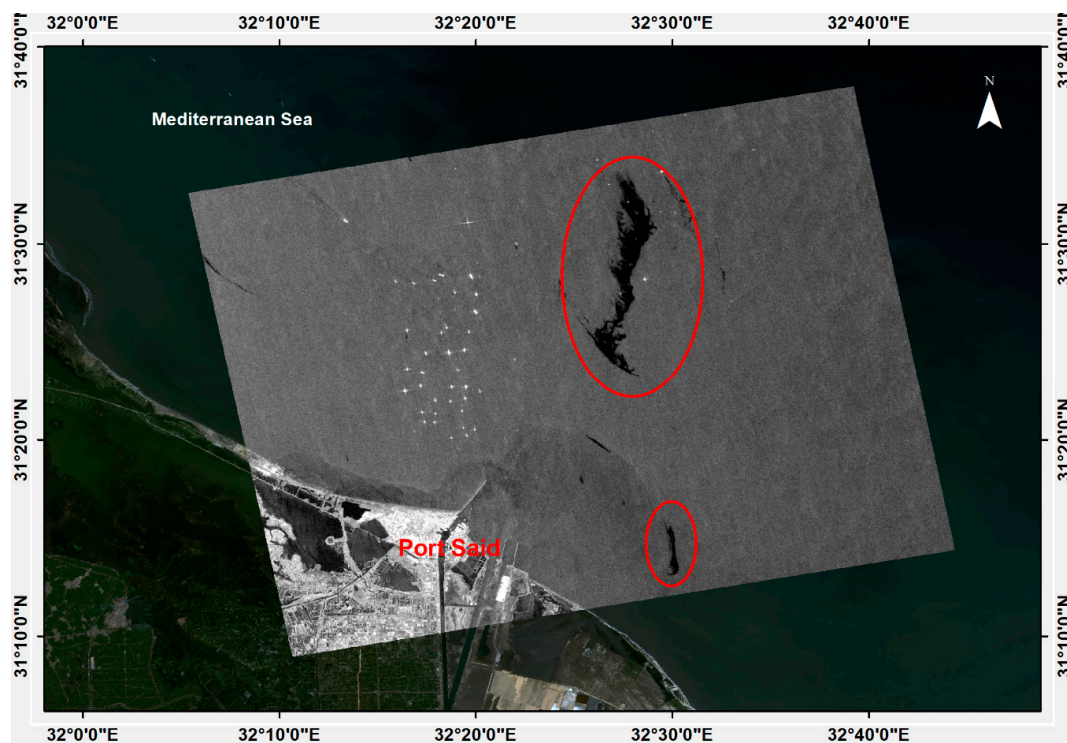


Figure 4. The largest oil spill event detected near the entrance of the Suez Canal.

An oil spill does not stand in its location, it migrates and moves as influenced by the wind and current. The processing cycle of the data to be clustered in relation to the wind vector is shown in Figure 5. The left side of the Figure 5A is the raw satellite data and when it is processed and modeled, it clusters the oil spill as shown in Figure 5B; superimposing the clustered oil spill on the satellite data is shown in Figure 5C; however, Figure 5D is together with the wind vector that influences the movement and pattern of the oil spill. The wind speed in this area ranges from 3–6 m/s which is appropriate for oil spill discrimination from SAR images [25] since a lower wind speed (calm water) could create false dark spots. This is because a light wind field can activate short gravity capillary waves and the minimum wind speed depends on the frequency of observation and the incidence angle.

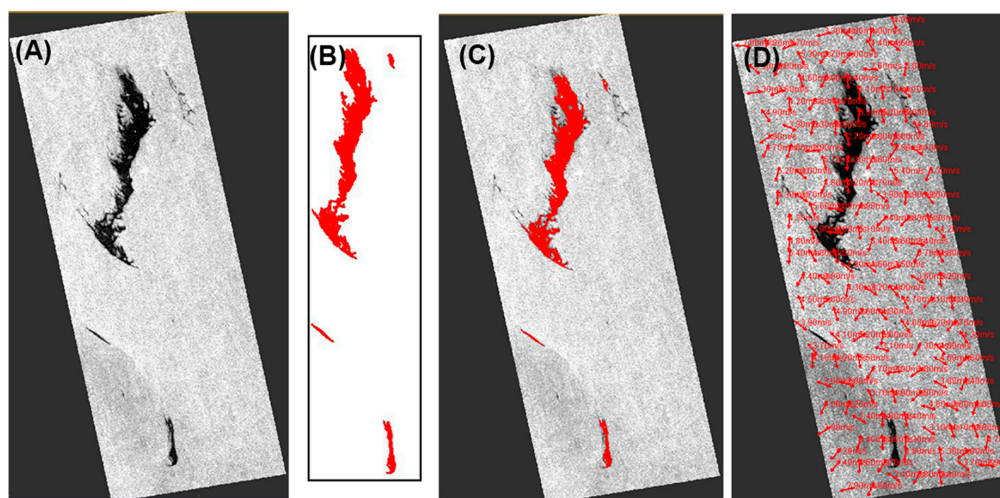


Figure 5. Oil spill clustering using a background window size of 500 pixels and a threshold shift of 3.5 dB and wind vector calculations (A) = raw data; (B) = clustered oil spill; (C) = superimpose of the clustered oil spillover raw data, and; (D) = superimposed by wind vector layer).

For spectral comparison between the dark spot of the oil spill and the surrounding environment of marine water and/or the vessels, a spectral profile plot over the spill was generated (Figure 6). The brightness of the captured image is a reflection of the properties of the target surface. It shows the comparison of reflectance between the normal seawater surface reflectance (range from -15 to -20 dB), the dark spot of oil (range from -23 to -26 dB), and the ships (range from 0 to 15 dB) that have very high reflectance. This range is relatively fit with the SAR image itself for this area of study. However, threshold ranges from (2 to 4 or 5 dB) is reserved for clean sea surface backscatter. A difference of more than 4 dB exists and this difference is used to determine the clustering threshold for the oil spill.

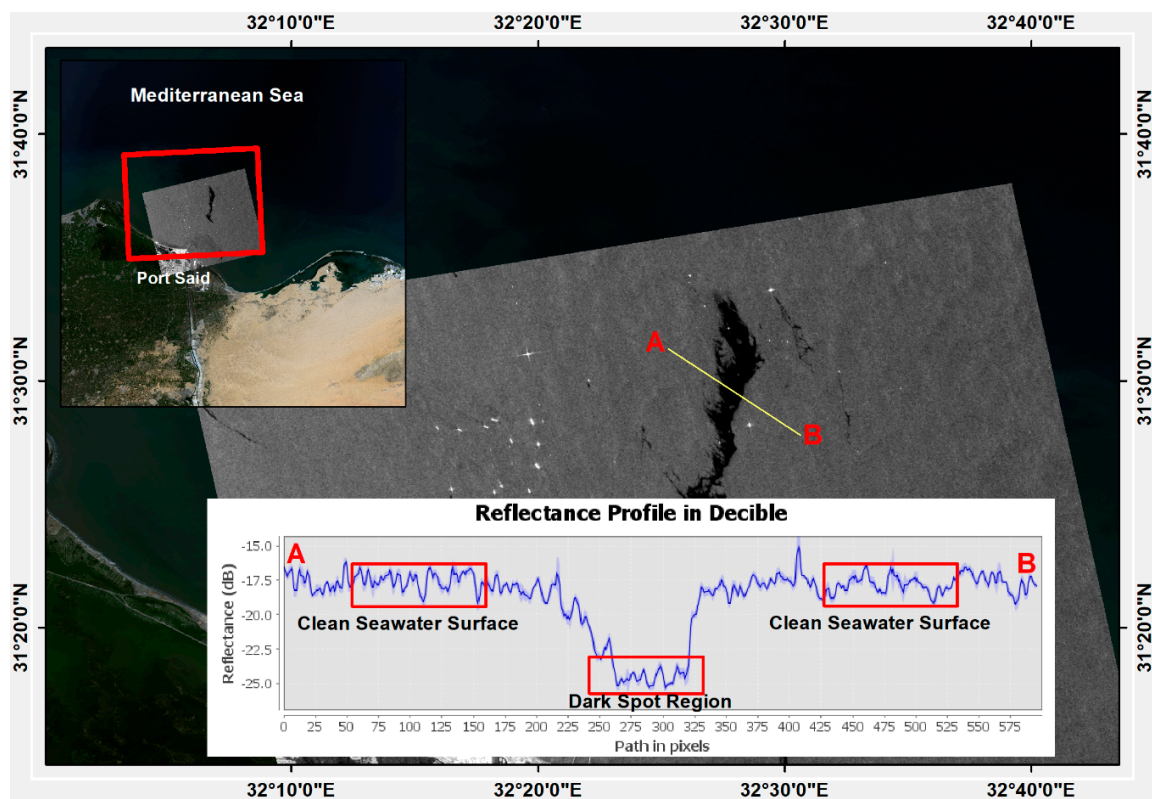
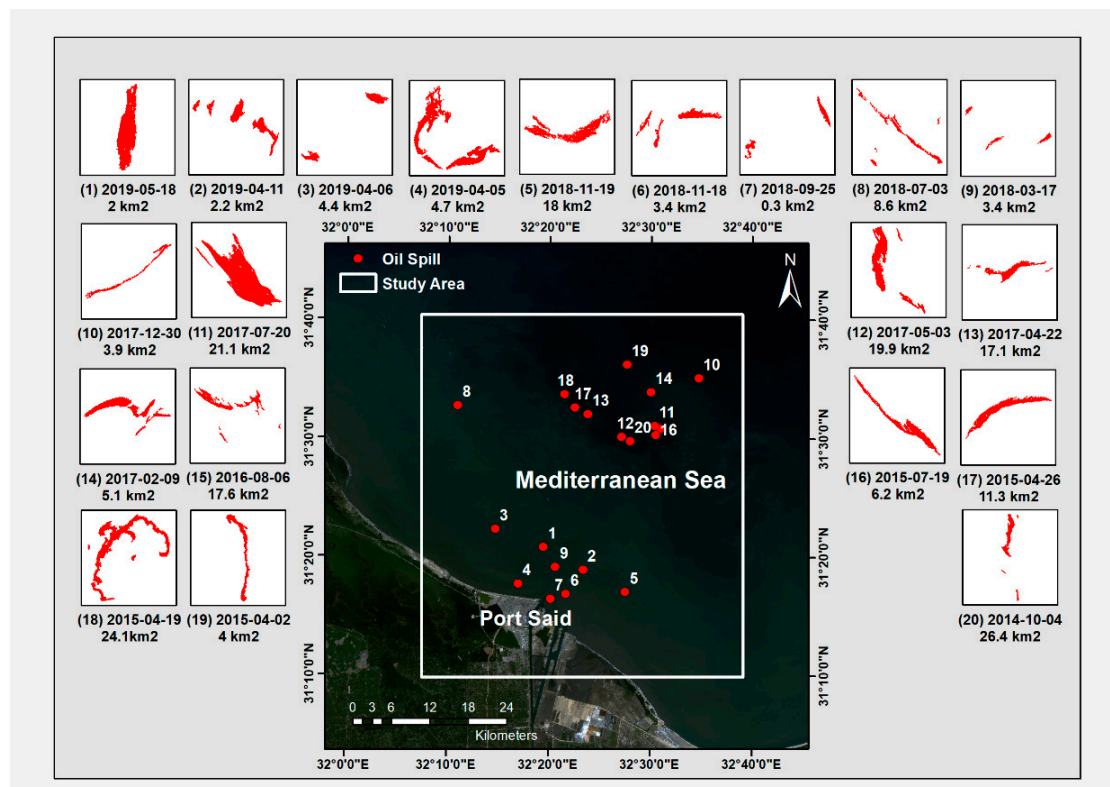


Figure 6. A profile plot for the spill event to monitor its reflectance, A and B = normal seawater reflectance, and the top 2 red squares are showing the reflectance of the clean seawater, the bottom red square outlines the reflectance of the dark spot area of oil pollution.

Table 2 lists the 20 oil spill observed cases that have been processed. The model has efficiently mapped the pattern and cluster of the oil spills in these cases (Figure 7). It is obvious that the 20 cases are located in the pathways of ships at the entrance of the Suez Canal. The oil spill cases are subjected, with high probability, to shipping vessels.

Table 2. Statistics of oil spill events within the period 2014–2019.

ID on Map	Date	Longitude	Latitude	Area (km ²)	Estimated Volume (m ³) Based on 1 μ m Thickness
1	2019-05-18	32°19'30"E	31°20'49"N	2	2
2	2019-04-11	32°23'24"E	31°18'55"N	2.2	2.2
3	2019-04-06	32°14'43"E	31°22'18"N	4.4	4.4
4	2019-04-05	32°17'0"E	31°17'42"N	4.7	4.7
5	2018-11-19	32°27'33"E	31°17'2"N	18	18
6	2018-11-18	32°21'43"E	31°16'51"N	3.4	3.4
7	2018-09-25	32°20'12"E	31°16'26"N	0.3	0.3
8	2018-07-03	32°10'58"E	31°32'44"N	8.6	8.6
9	2018-03-17	32°20'39"E	31°19'8"N	3.4	3.4
10	2017-12-30	32°34'44"E	31°35'5"N	3.9	3.9
11	2017-07-20	32°30'24"E	31°31'4"N	21.1	21.1
12	2017-05-03	32°27'10"E	31°30'9"N	19.9	19.9
13	2017-04-22	32°23'49"E	31°32'2"N	17.1	17.1
14	2017-02-09	32°29'60"E	31°33'54"N	5.1	5.1
15	2016-08-06	32°30'60"E	31°30'50"N	17.6	17.6
16	2015-07-19	32°30'31"E	31°30'17"N	6.2	6.2
17	2015-04-26	32°22'31"E	31°32'36"N	11.3	11.3
18	2015-04-19	32°21'28"E	31°33'42"N	24.1	24.1
19	2015-04-02	32°27'40"E	31°36'14"N	4	4
20	2014-10-04	32°28'0"E	31°29'46"N	26.4	26.4

**Figure 7.** Oil spill accidents within the period 2014–2019.

5. Validation

Oil spills usually appear for a short period of time especially if the volume of oil spilled is a small quantity such as that of illegal ship discharges. A field check is not an easy task and requires real-time monitoring using aerial surveillance to obtain data on the real incident of oil pollution. Therefore, a simple approach to validate the method and check the efficiency of the model is to reiterate it on a real recorded accident and compare the results. Recently, an oil spill incident happened on 11th of

October, 2019 at 5 a.m. local time in the Red Sea; the Sabiti oil tanker had an accident near Jeddah port in the Red Sea. Two reservoirs of crude oil on the ship were damaged and caused massive oil leakage to the sea [26]. This oil slick appeared in four raw Sentinel 1 scenes on 13th and 14th October as shown in Figure 6. When processed and reiterated, the model of the satellite data on these dates using a threshold of 3 dB clustered the oil spill in the Red Sea covering an area of about 1500 km² (Figure 8). The model mapped and identified the aerial coverage (cross-section of nearly 500 km long) and pattern of oil spill movement north and south of the location of the incident. The circulation pattern and movement of the oil spill were largely extended to the south of the incident (Figure 8). The model shows a significant level of detection of oil spill cases based on historical records of real cases with more than 90% of the detection of both large and small cases.

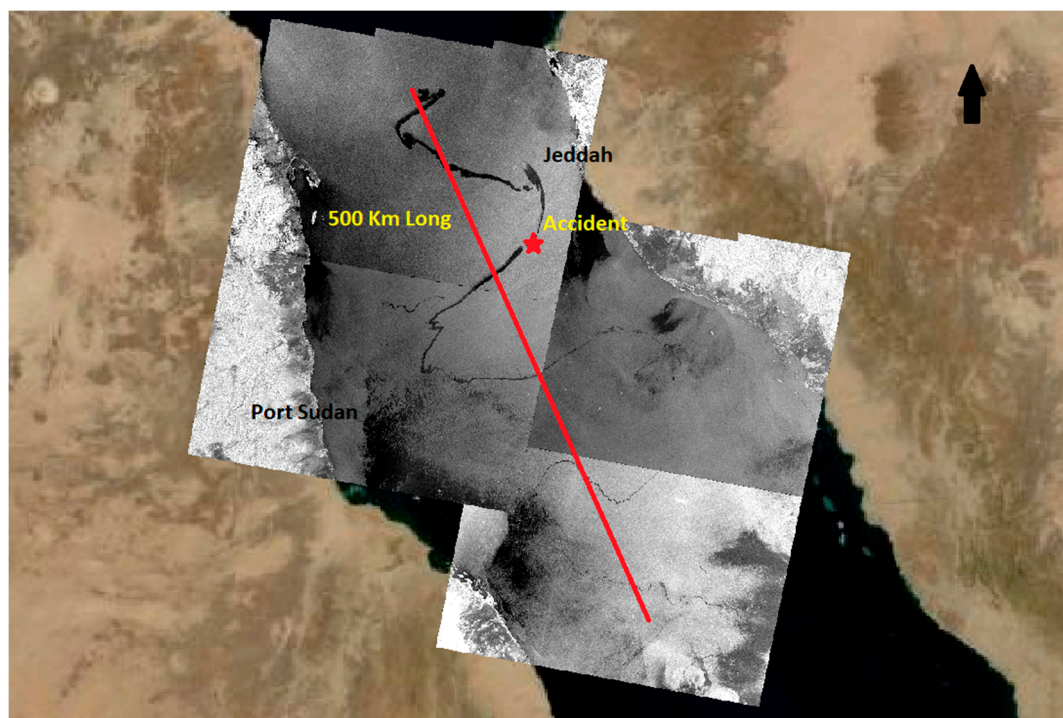


Figure 8. Oil spill extent of the Iranian oil tanker accident near the Saudi Jeddah Port.

6. Discussion

Oil spills in the area of study frequently occur and are relatively small, which is most probably indicative of illegal ship discharges. The oil spills varied in shape, size, and pattern. Most of the oil spills' patterns are elongated, which indicates a probable discharge during the movement of the ships. However, other cases are circular spills, which might indicate discharge during anchoring. Most of the detected spills are located in two zones; the first zone is at 7 km from the entrance of the canal and the second is about 30 km from the coastline, which marks a repeated behavior of the violated ships (Figure 9).

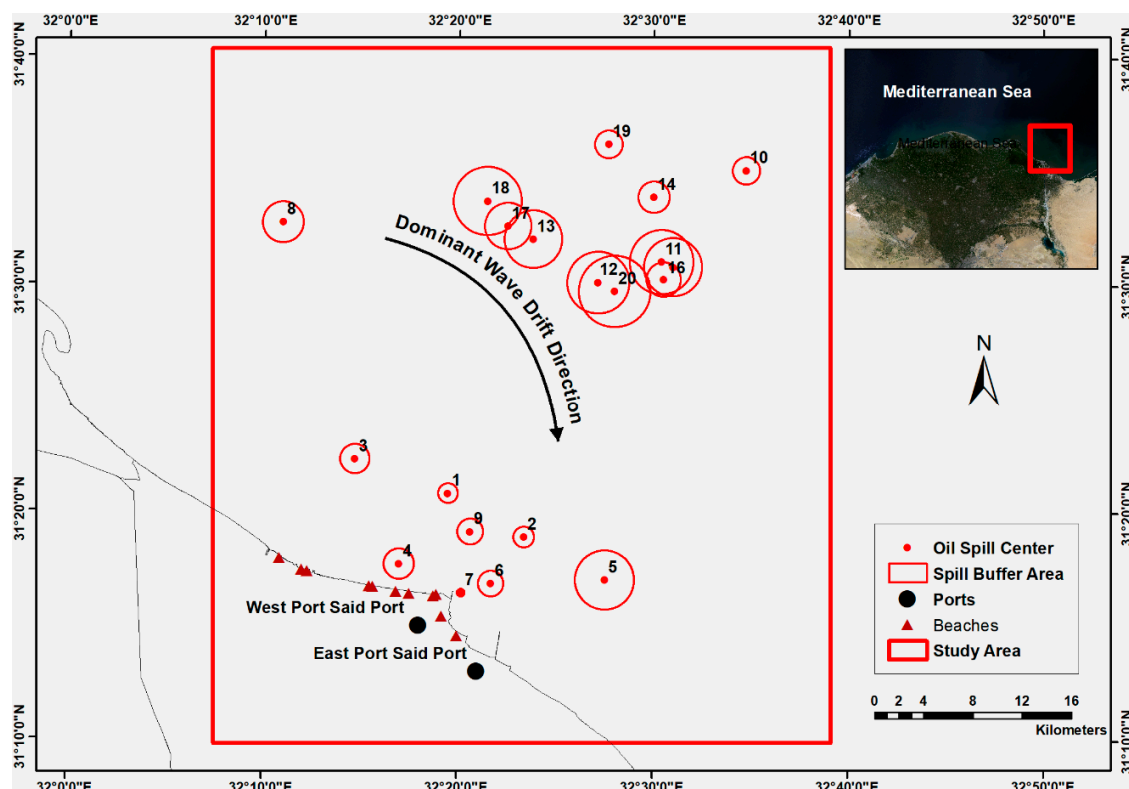


Figure 9. Hazards map of the oil spills near the Suez Canal entrance.

The 20 oil spill cases are within a few kilometers from the coastal zone of Port Said, which will have a direct impact on the ecosystems, social, and economic activities. The flow/current of water is supposed to drift such oil spills to the coastline creating a direct impact on society. The proposed direct hazards of this oil spill will be on tourism activities, industrial activities of fish farms and aquaculture, and other social activities near the coastal areas. The area is inhabited with nearly 1 million population with diverse social and economic activities. For example, the tourism activities engage more than 300 cruises of public ships and 200 yachts that visit Port Said every year. The number of summer tourists that visit Port Said beaches is nearly 400,000 people, which flourishes the tourism industry and creates income for the local community. Such high income from this activity is at risk from the possible oil pollution. More importantly, the area is heavily utilized for fish production, aquaculture, and the fish industry. This means that annual fish production in this area from the Mediterranean Sea is about 9000 tons, and nearly 2500 tons from Lake Manzala, 160 ton from Port Fouad and 17000 tons from licensed fish farms [27]. This industry is engaging a large number of people and contributes to the socio-economic development of the area. The oil pollution could, indeed, create pressure on this fishing activity and increase pressure on the ecosystem and fish production and industry. It might also, due to the wind and flow of the current that controls the drift to the southeast direction, create risks and hazards for the harbor (Figure 9).

The result of this model could be a solution for the operational robust model to monitor the oil spills in this dynamic area to alert decision-makers for prevention, remediation, and mitigation. The open data access policy by the European Space Agency is key for such a model and outcomes, which will create an impact on society and create a warning system for the preservation of the environment.

7. Conclusions

The study concludes that the north entrance of the Suez Canal encounters multiple oil spill occurrences from time to time along the navigation route. A period of five years has been analyzed and detected nearly 20 oil spill cases, which was effectively mapped with the largest oil spill covering

nearly 26 km² of the sea surface. The research study also proved the potentiality of SAR data together with the developed method to map an aerial coverage of oil spills. It could be robustly employed to develop an alarming system for oil spill detection and inform environmental agencies to create a contingency plan. The availability of Sentinel 1 SAR data is an important source in developing an advanced and wide range oil spill detection system. Matching the recorded oil spill cases with the ship's automatic identification system (AIS) data can help to find the responsible ships for past events. The detection model can be used for a fast alert of oil spill cases and a near real-time service, which can help to catch the liable ship red-handed.

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References

1. Brekke, C.; Solberg, A.H.S. Oil spill detection by satellite remote sensing. *Remote Sens. Environ.* **2005**, *95*, 1–13. [CrossRef]
2. Singha, S.; Bellerby, T.J.; Trieschmann, O. Detection and classification of oil spill and look-alike spots from SAR imagery using an artificial neural network. In Proceedings of the 2012 IEEE International Geoscience and Remote Sensing Symposium, Munich, Germany, 22–27 July 2012; pp. 5630–5633.
3. Fingas, M.F.; Charles, J. *The Basics of Oil Spill Cleanup*; Lewis Publishers: Boca Raton, FL, USA, 2001; ISBN 9781566705370; 9781420032598.
4. Franceschetti, G.A.; Riccio, I.D.; Ruello, G.; Siviero, R. SAR raw signal simulation of oil slicks in ocean environments. *IEEE Trans. Geosci. Remote Sens.* **2002**, *40*, 1935–1949. [CrossRef]
5. Alpers, W.; Holt, B.; Zeng, K. Oil spill detection by imaging radars: Challenges and pitfalls. In Proceedings of the 2017 IEEE International Geoscience and Remote Sensing Symposium, Fort Worth, TX, USA, 23–28 July 2017; pp. 1522–1525. [CrossRef]
6. Fotias, V. Oil Spills Detection and Identification with Synthetic Aperture Radar (SAR), GEO University. 2018. Available online: <https://www.geo.university/pages/oil-spills-detection-and-identification-with-synthetic-aperture-radar-sar> (accessed on 21 October 2019).
7. Arslan, N. Assessment of oil spills using Sentinel 1 C-band SAR and Landsat 8 multispectral sensors. *Environ. Monit. Assess.* **2018**, *190*, 637. [CrossRef] [PubMed]
8. Ferraro, G.; Trieschmann, O.; Perkovic, M.; Tarchi, D. Confidence levels in the detection of oil spills from satellite imagery: From research to the operational use. In *Proceedings of SAR Image Analysis, Modeling, and Techniques XII; Modeling, and Techniques XII*, SPIE Remote Sensing: Edinburgh, UK, 2012; Volume 8536, p. 85360G.
9. Data Application of the Month: Oil Spill Mapping|UN-SPIDER Knowledge Portal. Available online: <http://www.un-spider.org/links-and-resources/data-sources/daotm-oil-spill> (accessed on 24 October 2019).
10. Liu, Y.A.; MacFadyen, Z.G.J.; Weisberg, R.H. *Monitoring and Modeling the Deepwater Horizon Oil Spill: A Record-Breaking Enterprise*; AGU/Geophysical Monograph Series; the American Geophysical Union: Washington, DC, USA, 2011; pp. 195–271.
11. El-Magd, I.A.; El Kafrawy, S.; Farag, I. Detecting oil spill contamination using airborne hyperspectral data in the River Nile, Egypt. *Open J. Mar. Sci.* **2014**, *4*, 140. [CrossRef]

12. Kotova, L.; Espedal, H. Oil spill detection using spaceborne SAR—A brief review. In Proceedings of the 27th International Symposium on Remote Sensing Environmental, Tromso, Norway, 8–12 June 1998; pp. 791–794.
13. Patin, S.A. *Environmental Impact of the Offshore Oil and Gas Industry*; JSTOR Ecomonitor Pub.: New York, NY, USA, 1999; Volume 1.
14. How We Determine Oil Spill Volume—SkyTruth. Available online: <https://skytruth.org/oil-spill-reports/oil-spill-reporting-resources/how-we-determine-oil-spill-volume/> (accessed on 21 October 2019).
15. Zaki, M.S.; Ata, N.; Abdelzaher, M.F.; Hammam, A.M.M. Effects of environmental oil spills on commercial fish and shellfish in Suez Canal and Suez Gulf regions. *Life Sci. J.* **2014**, *11*, 269–274.
16. Nasr, A.H.; Ahmed, M.H. Detecting oil spills in the offshore Nile delta coast using image processing of ERS SAR data. *Environ. Aff.* **2000**, *23*, 5.
17. Alves, T.M.; Kokinou, E.; Zodiatis, G.; Radhakrishnan, H.; Panagiotakis, C.; Lardner, R. Multidisciplinary oil spill modeling to protect coastal communities and the environment of the Eastern Mediterranean Sea. *Sci. Rep.* **2016**, *6*, 36882. [[CrossRef](#)] [[PubMed](#)]
18. Shaltout, M.; Tonbol, K. Modeling of wave propagation off Damietta-Port Said Coast, Egypt. *J. Arab Inst. Navig.* **2011**, *27*, 56–67.
19. Fletcher, M.E. The Suez Canal and World Shipping, 1869–1914. *J. Econ. Hist.* **1958**, *18*, 556–573. [[CrossRef](#)]
20. EO Browser|Sentinel Hub. Available online: <https://www.sentinel-hub.com/explore/eobrowser> (accessed on 21 October 2019).
21. Richards, J. *A Remote Sensing with Imaging Radar*; Springer: Berlin, Germany, 2009; ISBN 9783642020193.
22. Misra, A.; Balaji, R. Simple Approaches to Oil Spill Detection Using Sentinel Application Platform (SNAP)-Ocean Application Tools and Texture Analysis: A Comparative Study. *J. Indian Soc. Remote Sens.* **2017**, *45*, 1065–1075. [[CrossRef](#)]
23. Lee, J.-S. Speckle analysis and smoothing of synthetic aperture radar images. *Comput. Graph. Image Process.* **1981**, *17*, 24–32. [[CrossRef](#)]
24. Earth Observation ServicesCleanSeaNet service-EMSA-European Maritime Safety Agency. Available online: <http://www.emsa.europa.eu/csn-menu.html> (accessed on 14 October 2019).
25. Solberg, A.H.S.; Volden, E. Incorporation of prior knowledge in automatic classification of oil spills in ERS SAR images. In Proceedings of the IGARSS'97. 1997 IEEE International Geoscience and Remote Sensing Symposium Proceedings. Remote Sensing—A Scientific Vision for Sustainable Development, Singapore, 3–8 August 1997; Volume 1, pp. 157–159.
26. Iran Says Oil Tanker Hit by Two Missiles off SAUDI Arabia Coast|Financial Times. Available online: <https://www.ft.com/content/2ae8d55a-ebef-11e9-a240-3b065ef5fc55> (accessed on 24 October 2019).
27. Mehanna, S.F.; Haggag, H.M. Port said fisheries: Current status, assessment and management. In Proceedings of the 3rd Global Fisheries and Aquaculture Research Conference, Foreign Agricultural Relations (FAR), Cairo, Egypt, 29 November–1 December 2010.



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