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Monitoring Oil Spills Offshore the United Arab Emirates Using Multi Satellite Data

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Abstract

The paper discusses sea oil pollution detection, statistics and mapping in the Arabian Gulf waters, offshore the United Arab Emirates by using multi- satellite data with particular focus on SAR data from different platforms. The work is roughly divided into four main steps. Possible oil slicks are first identified from each image. Next, the slick is analyzed to separate natural slicks from possible oil spills. The later are subjected to further re-examination so that all possible oil spills are identified and mapped. The overall statistical results are then complied and percentages of occurrences of each spill type are calculated. Finally, spatial oil spill distribution maps in the Arabian Gulf waters; offshore the United Arab Emirates are derived and compiled in an "oil atlas". The results show very good agreement with shipping routes, ships anchoring areas and oil production facilities.

1 Introduction

In spite of rigorous controls, deterioration of marine water quality, especially in waters subject to heavy shipping, still continues at a high rate. Oil spills can cause substantial damage to the marine environment and has created a growing concern for necessary prevention measures. Thousands of tons of oil are spilled into our seas every year from ships, rigs, land runoffs, or natural seepage from seabed oil structures. It has been reported that operational tanker oil discharges (i.e. dumping of oil during tanker cleaning operations) form about 45% of the total ocean oil pollution in the world while ship accidents and oil platform accidents contribute only 5% and 2% respectively (ESA, 1998). Hence, deliberate oil emissions from ships impose a much greater long-term threat to the ocean environment than that from big ship accidents. Monitoring illegal ship discharges is thus an important component in ensuring compliance with the marine protection legislation and the general protection of coastal environments (Jensen *et al.,* 1992; Perry *et al.* 2001; Lu 2003; Essa *et al.,* 2005).

The Arabian Gulf is crowded with rigs and platforms engaged in the exploration of oil and natural gas. In addition, more than 30,000 oil tankers representing about 30% of the world's oil tankers operating in the Gulf region pass through the strategic strait of Hormuz every year, nearly a quarter of the world's consumed oil. Locally, the United Arab Emirates (UAE) produces about 2.2 million barrels of oil per day (bopd), (Bruce 2002). Over half of this oil is produced offshore. The majority of the oil produced in Abu Dhabi is exported via ship. On a regional basis, 65% of the world's proven reserves are located in the Gulf and Arabia area (Alsharhan and Narin, 1997). In 1999, the daily average production of oil out of the region was 21 million bopd, (BP Amoco 2000). Fujairah on the east coast of the UAE has become one of the world's largest bunkering facilities, servicing tankers moving in and out of the Gulf.

In 1996 it was estimated that 1.2 million barrels of oil are spilled annually in the Arabian Gulf Region (Al-Majed, *et al.,* 2000). Surface currents in the eastern Arabian Gulf move in a counterclockwise gyre, bringing oil that has been spilled in the lower Gulf waters to the UAE Coast (Bruce 2002). Over the last several years there have been a number of spills in UAE waters (Table 1). However, the UAE's largest oil spill has occurred in 1994 when 16,000 tones of Iranian crude oil caused serious damage to the country's eastern coastline (Fujairah) and its important fishery industry. Residents fled Fujairah town, the tiny UAE emirate, on the Gulf of Oman in the Indian Ocean, returning only after the spill was cleared with the use of chemicals after a huge operation.

Table 1: Major oil spill incidents offshore UAE

No	**Date**	**Volume of spilled oil (tones)**	**Oil type**	**Location**
1	2001/04/13	1,300	Fuel	26 miles west of Dubai
2	2001/01/14	1,300 – 1,500	Fuel	1 mile offshore Jabal Ali
3	2001/01/24	300 – 900	Heavy	7 mile NE offshore Abu Dhabi
4	1998/01/07	5,000 – 10,000	Crude	5 miles offshore Ajman
5	1994/03/30	16,000	Light	9.6 miles offshore Fujairah

Oil pollution surveillance and mapping over a large sea area has become operational with the various remote sensing satellites orbiting the earth. Space-borne synthetic aperture radar (SAR) has, in particular, become a very popular tool for ocean oil slick monitoring due to its wide area coverage and cloud-free, day and night operation. Optical satellite images can assist in certain difficult situations. However, visible satellite systems experience lack of positive oil identification with high number of false alarms which generally limits their use for detection of the oil spills. This is attributed to sun glint, wind sheen, bottom features, cloud shadows, and biogenic material (Goodman, 1989 and 1992; Fingas et al., 1990 and 1992). Environmental conditions such as precipitation, fog, and the amounts of daylight present also may pose additional problems in optical images. In such difficult cases SAR is used, when the oil cannot be seen or discriminated against the background.

Some very successful examples of SAR applications in marine oil spill detection have been documented, such as the practical rules of thumb using wind history information when analyzing SAR images for potential oil spills monitoring in Norway (Espedal and Wahl 1999) and the ERS SAR marine oil spill applications in south-east Asian waters (Lu 2003). Successful oil slick detection is based on a thorough consideration of all kinds of available image and contextual information including slick shape, size, dBvalue, edge gradient, texture, orientation, wind, current, ship lane, rigs/ships, natural seepage, etc. Pavlakis et al. (1996), after interpreting 190 ERS-1 SAR frames covering the Mediterranean coastal zone, found that the frequency of 'deliberate' oil spillage was much higher than that from ship accidents. They also identified those areas with a higher occurrence of oil spills for the planning of further intensive monitoring schemes based on ERS SAR. Gade and Ufermann (1998), after analysing more than 400 ERS-2 SAR images over the southern Baltic Sea, the North Sea, and the Gulf of Lions in the Mediterranean Sea, indicated that these seas were most polluted along the main shipping routes. In a recent study on ocean oil spill statistics using ERS SAR imagery, Lu (2003), discussed ocean oil pollution detection, statistics and mapping in south-east Asian waters. After analyzing thousands of scenes over the study area, he derived spatial oil spill distribution maps in the south-east Asian waters and found very good agreement with shipping routes as well as in situ data in the region. However, this study does not take low and high wind conditions into account.

Objectives of this study will be 1) the development of a simple methodology for sea oil pollution detection in the Arabian Gulf; 2) the identification of vulnerable areas to oil spills pollution and lay down a strategy for future monitoring for the protection of marine environment and; 3) the compilation of all relevant geographic and textual data into a standard GIS format (e.g. Arc GIS) for the West and East coasts of the United Arab Emirates.

2 Materials and Methods

2.1 Study Area

The study sites are located at longitudes 52°E - 56°45'E; and latitudes 24°15'N - 26°N, they cover two areas -one offshore of Abu Dhabi and northeast wards to Ras al Khaimah in the Arabian Gulf, and the other offshore Fujairah in the Gulf of Oman (Figure 1).

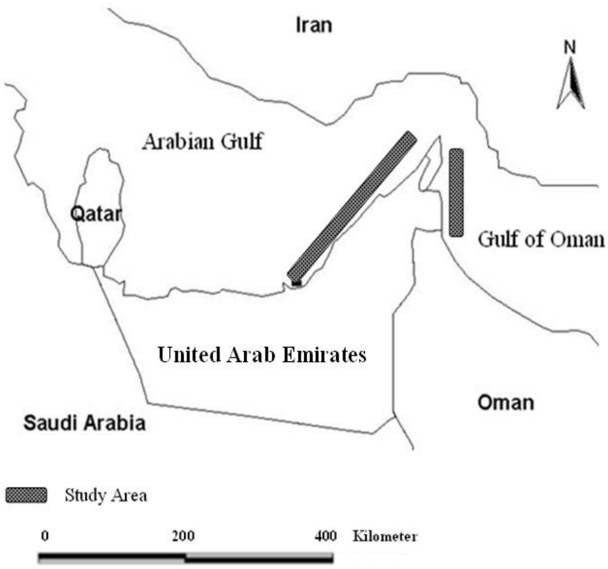

Figure 1: Study Area

2.2 Data set

A total of 378 satellite images (Optical and SAR) have been examined during this study (Table 2). ERS-1/2, RADARSAT, and ENVISAT C-band SAR data has been used for the great majority of oil spill detection operations. SAR system is well known and proven since a long time for its capability in detecting oil slicks over the sea surface. In addition, the continuous available coverage by SAR images of the study area day and night in almost all years was a determining factor in this regard. Optical images of the year 2000 were used as a substitute, because of non availability of SAR coverage during that period.

Therefore, we looked for all available image data archives and selected more than one hundred SAR images derived from different platforms that covered most of the offshore waters of the UAE. To evaluate their suitability for slick detection, historical wind conditions for corresponding SAR images were obtained. For each acquisition date, surface wind speed histories were reconstructed using historical records. Finally, the digital image processing software ERMapper version7 was used in all study phases.

Table 2: Satellite imagery investigated during the study project

SATELLITE SYSTEM	NUMBER	SENSOR	Band Wavelength	Ground Resolution	DATE
JERS-1 (Japan)	64 scenes	SAR	L (23.5cm)	18m	May 1992– July 1996
Shuttle Imaging Radar	37 segments	C/X-SAR	C (5.6cm), X (3cm)	10m	1998
ERS-1/2 (EU)	15 scenes	AMI (A, D)	C (5.6cm),	25m	April 1996 – May 1999
Radarsat (Canada)	3 scenes	SAR (A, D)	C (5.6cm),	25m	Oct. 2001 – May 2002
Envisat WS (EU)	7 scenes	ASAR (A, D)	C (5.6cm),	150m	July 2003
Landsat-7 ETM+ (US)	15 scenes	VIS, IR, TIR	0.525-0.605 0.63-0.69 0.75-0.90 10.40-12.5μm	30m, 60m	2000
JERS-1 OPS (Japan)	92 scenes	VNIR,	0.52-0.60 0.63-0.69 0.76-0.86 1.60-1.71μm	24m	June 1992 – May 1995
Terra ASTER (Japan/US)	95 scenes	VNIR	0.52-0.60 0.63-0.69 0.76-0.86 0.76-0.86μm	15m	June 2001 – July 2002
Shuttle Handheld Camera Photographs	50 photos	Shuttle Photograph			1998

2.3 Methodology used

The analysis of each single image is performed by a specialist using photo-interpretation techniques. Even though several studies have been conducted using semi-automatic methods (Topouzelis, K., *et al.,* 2002; Karathanassi, V., *et al.,* 2007), nevertheless the procedure of detecting oil spills still relies on photo-interpretation techniques from an expert in oil spill detection. The procedure includes the following main argument: an overall assessment of image quality and suitability for slick detection is first conducted; if the image proves suitable for oil slick detection then the identification and mapping process of possible oil slicks in the area is implemented. The methodology applied to SAR images is illustrated in figure 2 and detailed in steps 1 to 4 below. Criteria used for the selection of satellite imagery and slick analysis are summarized as follows:

> “If at any time during the previous 24 hours the wind speed exceeded 7 to 8 meters per second? then this is potentially an oil slick that is identified and accounted for in Step 4. Conversely, if during the previous 24 hours the wind speed never exceeded 8 meters per second? the slick is checked against well known shapes of some natural phenomena (Step 2). If no match is found, the location of the slick configuration is compared against the characteristic signature of known natural seepages (typical droplet shape), if a match in location and/or configuration was found, the slick is classified as natural slick in Step 3 and accounted for in Step 4. Finally, the slick location is compared to known locations of oil installations, platforms, anchorage area and ship routing. If a match is found, the slick is classified as potential oil spill in Step 3 and accounted for in Step 4”.

The methodology is adopted after Espedal and Wahl 1999, and is illustrated by the decision tree flow chart below (figure 2) which is composed of the following main steps:

Step 1: Slick detection

The detectability of oil slicks depends on the ocean surface wind speed. If the wind speed is too low (< $3ms^{-1}$), the sea surface background does not have sufficient roughness to contrast with that of oil films. On the other hand, if wind speed is too high (typically above 12 ms−1), oil slicks can be dispersed by the surface waves and disappear below the sea surface. A slick that remains on the sea surface at wind speeds above 7–8 ms^{-1} is highly likely to be oil since all types of natural slicks will disperse in such strong winds (Scott 1986).

The most difficult work is to distinguish **oil slicks from natural films**. Therefore, all available wind information (e.g. wind speed, wind direction and wind history), in addition to other contextual and slick characteristics information is taken into account in identifying an oil slick. A real mineral oil slick normally has a smooth border, a sharp edge and a dumping ratio in the range of 5–8 dB (Wahl et al. 1994). In this study, any slick in a SAR image which is significantly darker (> 4dB difference) than the surrounding sea surface signature, is classified as a possible oil spill and is therefore further investigated (Wismann *et al*. 1998, Espedal and Wahl 1999).

Step 2: Natural slick identification

Slick characteristics including shape, size, dB value, and texture; besides contextual information including instantaneous wind, current, rigs location, natural seepage locations and ship routes information is analyzed to separate natural slicks from an oil spill. A SAR image depicts the ocean surface at a given point in time by sensing capillary and short gravity waves (approximately 7 cm long for the ERS-1 C-band SAR).

Step 3: Oil Spill identification

This step is the most delicate step to separate oil spills from all other look-alikes, including natural film, natural seepage, wind sheltering by oil rigs, and threshold wind (< $3ms^{-1}$). Here wind information involving wind speed, wind direction and wind history is investigated to isolate all look-alikes.

Step 4: Slicks statistics

Here slicks are categorized into 5 different types based on our observation of the most frequently observed slicks on SAR images in the Arabian Gulf. Detailed of these different types will follow in the Results and discussion section below.

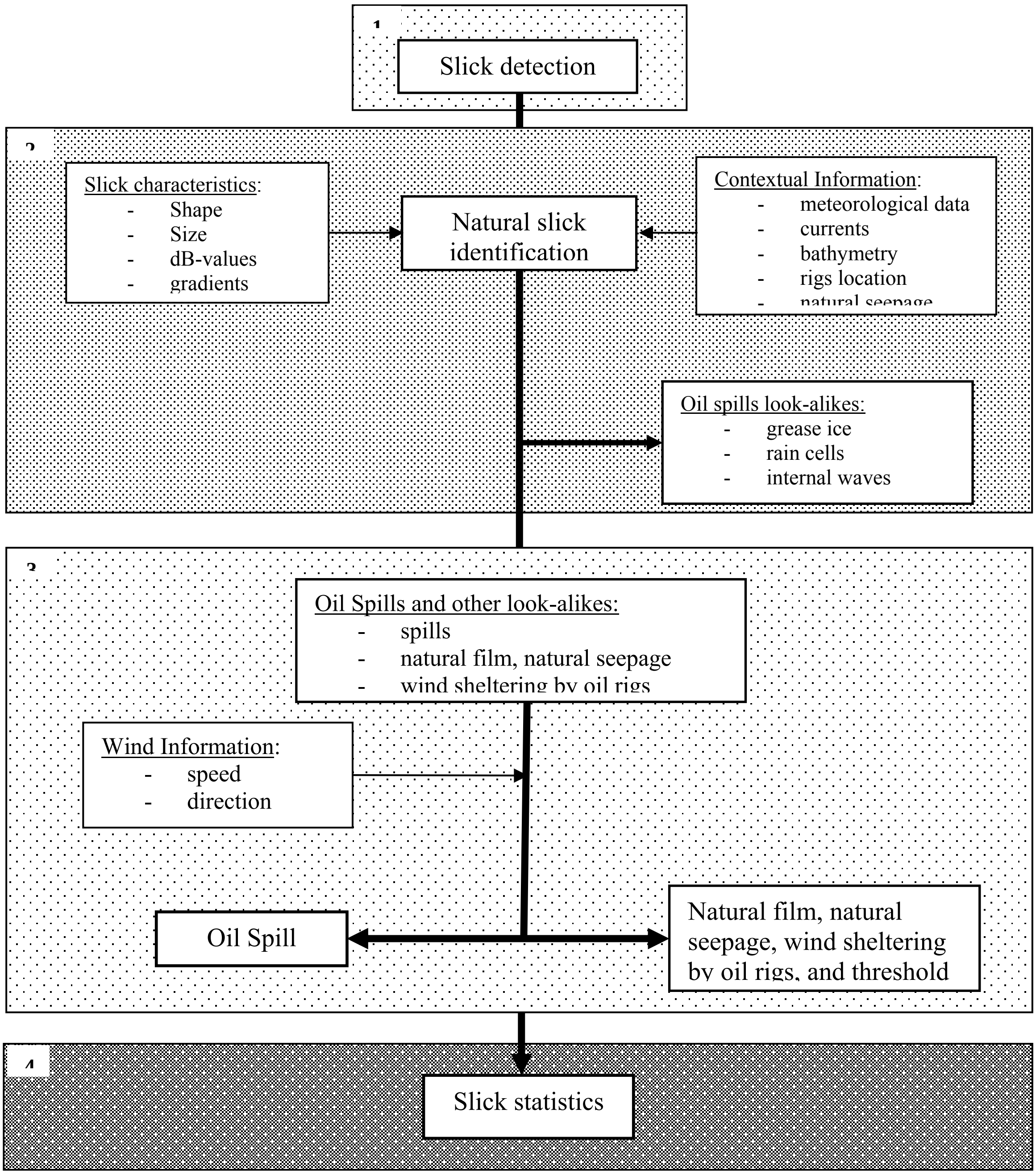

Figure 2: Flowchart showing oil spill detection analysis procedure

3 Results and Discussion

The actual study is probably the first attempt at marine oil pollution mapping with various satellite data over large areas of the Arabian Gulf. The study further compiled an oil spill Atlas offshore the UAE and mapped all kinds of oil spills (Issa 2008). For the period 1992 – 2003 a total of 378 satellite images covering around 800 kilometers of the West and East coasts of the United Arab Emirates were analyzed and more than 607 possible spills have been detected. Figure 3 and figure 4 show examples of the man made oil slicks including: discharged from moving vessels, leakage from oil production facilities, spills from anchoring vessels as well as oil spills from natural seepage. While examples of oil spill look-alikes are shown in figure 5.

3.1. Slick types

Five types of slicks could be classified during this study as detailed below:

a) Spills discharged from moving vessels. This type is mainly recognized by the shape of the slick. Indeed, if oil is released from a moving source, e.g. a tanker, the development of the slick shape is mostly influenced by the ship speed and direction. These slicks are generally tail slicks, since the length in the ship direction usually greatly exceeds the width, and the wind and ocean current fields will need some time to change the slick shape. Any changes in ship direction will result in bends on the slick, provided that the amount of spill is sufficient to keep the slick connected. This has been observed in several ERS SAR images (Hamre et al. 1997). However, in the case of long (more than a few kilometers) straight-lined slicks, the probability for having the same wind and surface current direction in a longer period is small. Such long, straight slicks are usually caused by moving point sources (figure 3). Four main contaminated areas were identified: i) offshore Fujairah and Khor Fakkan and the Gulf of Oman; ii) offshore Dubai, Fateh oil fields, Mubarak Oil Field, Ziruk Island, and Abu Musa Island; iii) the Strait of Hormuz; and iv) offshore Abu Dhabi and Ruwais terminal facility;

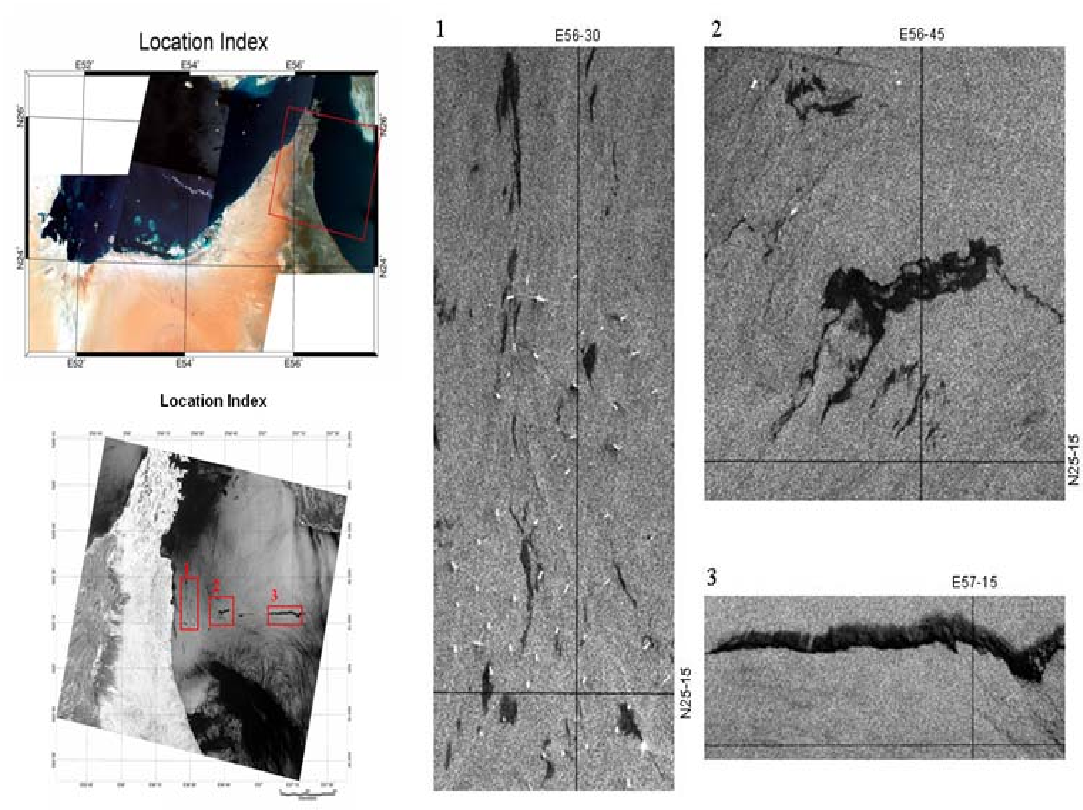

Figure 3: Radarsat SAR Wide mode 1 image of the west coast of the Gulf of Oman, acquired on 16 March 2002. Radarsat SAR wide mode image cover 150 km of the earth surface swath. Along the coast from Khor Fakkan to Dibba, slicks lie parallel to the shoreline (Sub-scene 1). Sub-scene 1 shows anchoring vessels in the Fujairah Offshore Anchoring Area. Oil slicks are even observed within the area near to anchored vessels (Sub-scene 2). In the middle of the Gulf of Oman, quite a large oil spill is observed (Sub-scene 3). This oil trail is more than 40 km long. A ship traveling westward with discharging oil before entering the anchoring area. Damped oil is dispersed with time and form a wide trail.

b) Spills from anchoring vessels. This is mainly found offshore Fujairah, Dibba and Khor Fakkan and the Gulf of Oman (figure 3);

c) Spills caused by leakage from existing production facilities. This type is mainly recognized by the fact that if oil is spilt from a fixed point source, it will move with certain percentage of the wind speed, to the right of the wind direction (Bern 1993), provided that no (strong) surface current is present and that no other factors have a great influence on the spread pattern. Performing GIS overlay analysis with known oil production locations helped locating affected areas (figure 4). Three main areas were identified: i) offshore Abu Dhabi -Sir Bu Nu'air Island and Umm Shaif Oil Field; ii) offshore Dubai and Umm al Qaiwian -Fateh and Mubarek oil fields and; iii) Abu Musa Island;

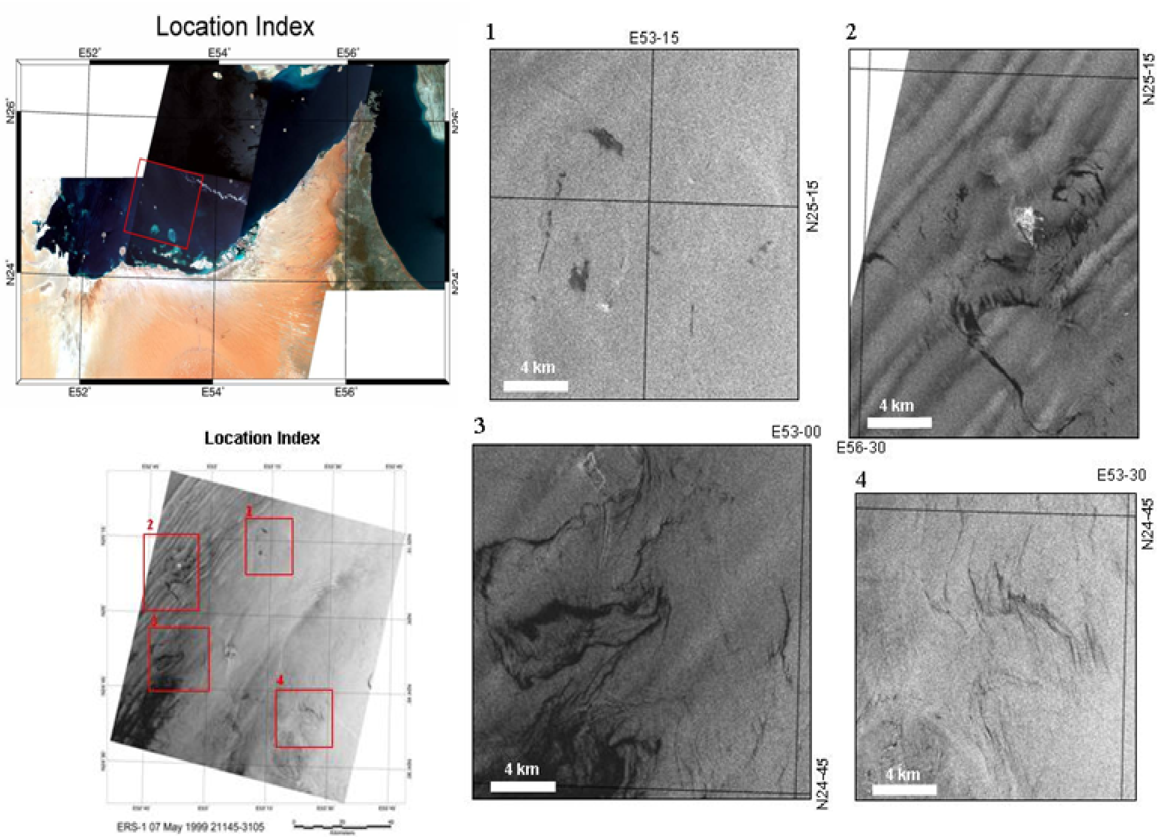

Figure 4: ERS-2 SAR image shows potential oil slicks around Das Island and Umm Shaif Oil Field as well as to the south of Qarnein Island, offshore Abu Dhabi. The image was observed on 7 May 1999. Atmospheric gravity waves are seen in the upper left of the image. Sub scene 1 shows potential oil spill around Umm Shaif Oil Field. Bright spots on the image represent production facilities. Sub scene 2 shows Das Island and surroundings where potential oil spill is widely observed. Qarnein Island is located near the upper edge of the sub scene 3. Older slicks originated from oil slicks can be observed. Parallel bright lines elongating from the island represent sea floor topography. Northeast of Umm Al Anbar Oil Field shows natural film slicks caused by Langmuir circulation of surface wind (sub-scene 4) .

d) Natural seepage slicks. Split from the sea floor through faults or fractures associated with the structure; typical "dog-leg" shape, covered by oil films except when strong wind blows and disperses oil films (figure 5). Mainly two areas were affected: i) offshore Abu Dhabi, Sir Bu Nu'air Island, Zakum Oil Field, Umm Shaif and Qarnein Island and; ii) Ziruk Island to Fateh Oil Field;

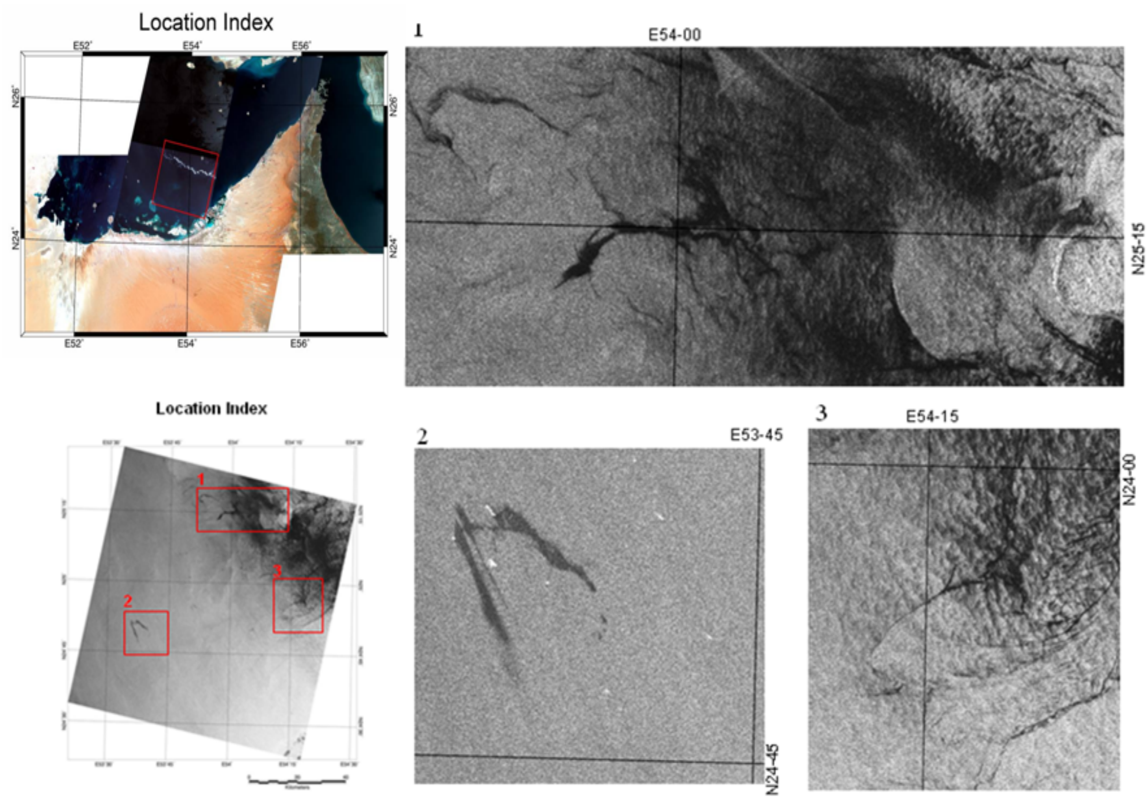

Figure 5: ERS-2 SAR image shows potential oil slicks at Zakum Oil Field and natural oil seepage at Mandous area, west of Sir Bu Nu'air Island, Umm Shaif and old slicks at south of Qarnein Island, offshore Abu Dhabi Emirate. A slick observed at cross point of longitude E54 and latitude N25-15 is potential natural seepage slick (sub-scene 1). Sub-scene 2 shows potential typical "dog-leg" shape oil spill at Zakum Oil Field. Bright spots on the image represent production platforms. Slicks were spread along the direction of wind and/or surface current. A weak contrast to surrounding water means that oil film was very thin and amount of oil was small. Sub-scene 3 is an example of oil spill look-alikes. The image was acquired on 23 May 1999.

e) Natural films. Algal bloom, ship wake, wind wakes, internal waves, coastal upwelling region, wind calm region, upwelling region (figure 5). Mainly found offshore Abu Dhabi Emirate, Zakum Oil Field. Mandous area, Umm Shaif, south of Qarnein Island, Das Island. Umm Al Anbar Oil Field. Sir Bu Nu'air Island.

3.2. Slick statistics

Statistical analysis was conducted to determine percentages of occurrences of each slick type in the study area (figure 6). Analysis revealed that almost half of the oil spilled offshore the UAE (48 %) was illegal discharged oil by moving vessels. Shipping routes bordering the UAE are the most affected areas including the offshore area running parallel to the coast of Abu Dhabi, Dubai, Sharjah and Ajman, where intensive oil production activities exist, and the routes through the Strait of Hormuz. Second, oil spills from natural seepage (17 %) affecting areas offshore Abu Dhabi near Sir Bu Nu'air Island, Zakum Oil Field, Umm Shaif and Qarnein Island. Next, the leakage from oil production facilities (13 %) affecting areas of intense oil production such as: offshore Abu Dhabi -Sir Bu Nu'air Island and Umm Shaif Oil Field as well as offshore Dubai and Umm al Qaiwian -Fateh and Mubarak oil fields. Finally, anchoring vessels offshore Fujairah anchoring area spilled 7 % of the total slicks detected in the study area. The remaining 15 % were identified as slicks from natural films such as: Algal bloom, ship wake, wind wakes, internal waves, coastal upwelling region, wind calm region and upwelling region; mainly found offshore Abu Dhabi Emirate.

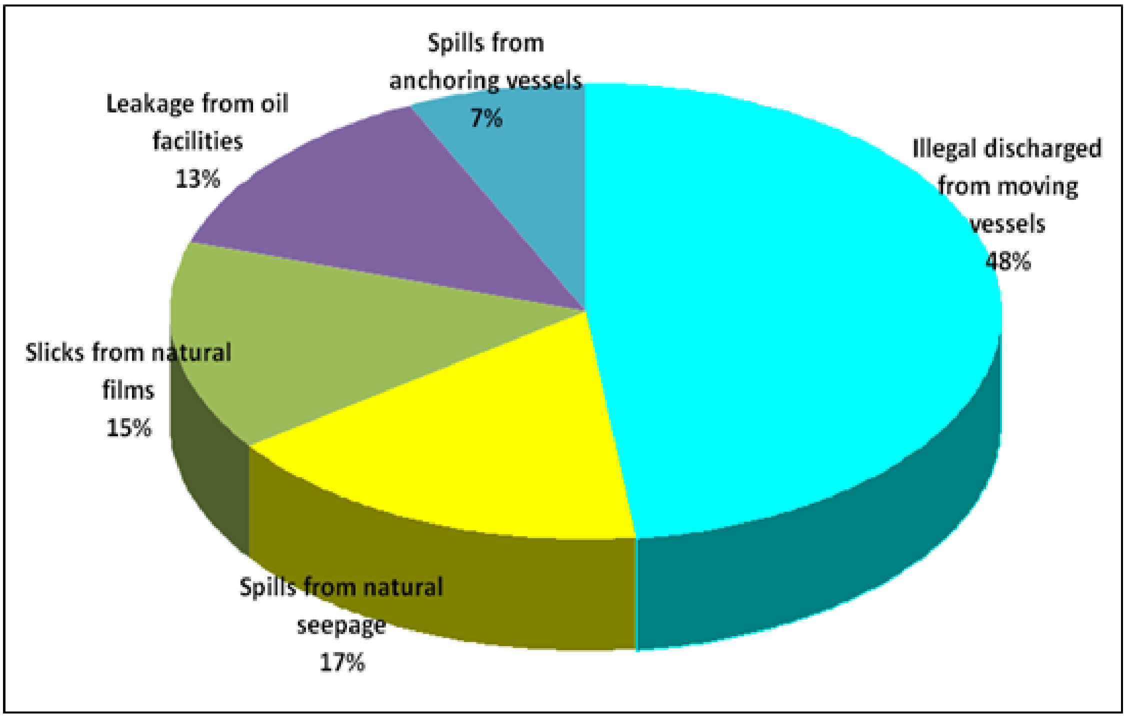

Figure 6: Statistics of oil slick types encountered in the study area.

3.3. Worst oil polluted areas

Worst oil polluted areas were highlighted using all available actual and historical satellite data as demonstrated in the different case studies below.

3.3.1. Case 1: Offshore Fujairah

The manual interpretation results indicate that certain coastal areas of the UAE face frequent oil spills. Striking examples of oil slicks are shown on figure 7, offshore Fujairah (centered at the coordinates 25°30'N/56°25'E). Here considerable spill concentrations have been found within successive JERS-1 OPS, Landsat-7 ETM+ images and ERS-1/2 SAR browse images. Figure 7 compares images from 29 June 1992, 21 May 1995 and 28 May 2000 for the same area of offshore Fujairah. Oil discharged from both anchored and moving vessels can be observed in each image. Immediately after discharging flush ballast water, the simmering water surface can be seen as bright silver to gray colour patches on the surrounding water. Based on the size of the image pixel, most of the vessels are super tankers whose hull is more than 300 m in length.

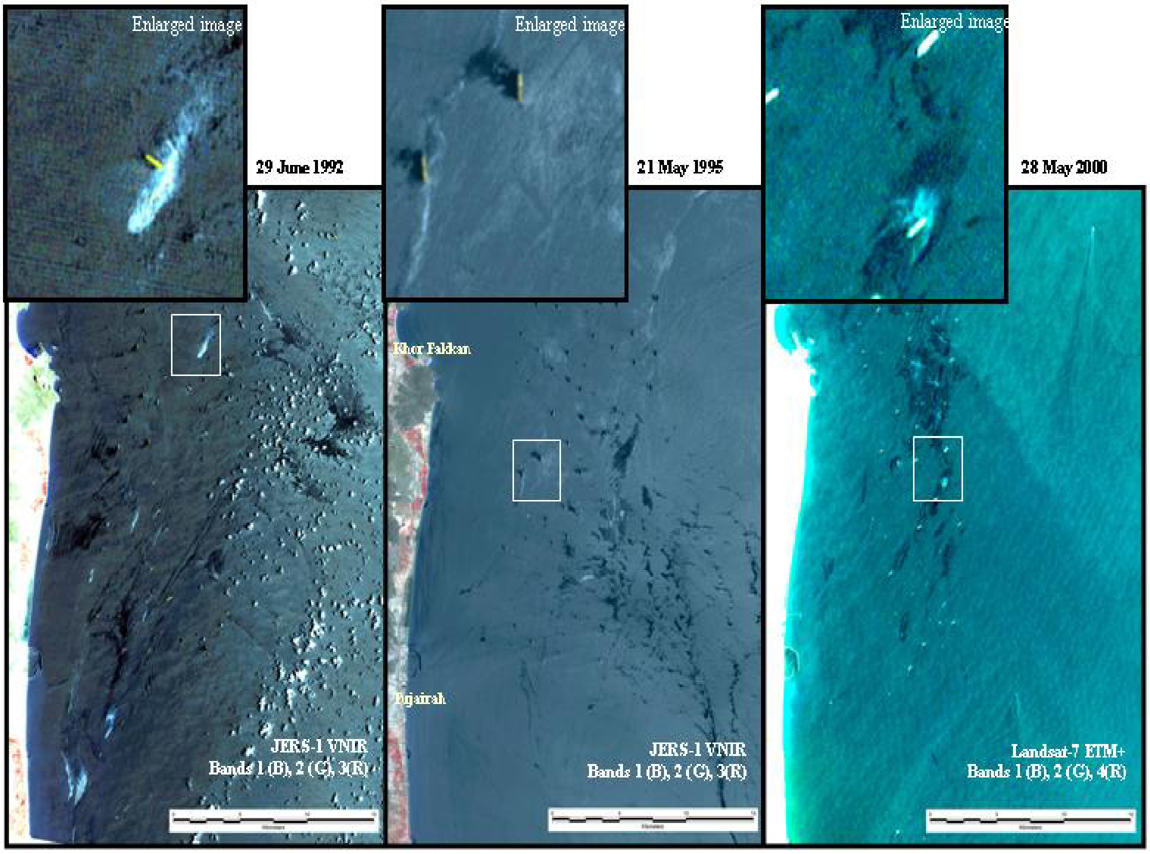

Figure 7: JERS-1 OPS and Landsat-7 ETM time sequence images, Fujairah Offshore Anchorage Area in the Gulf of Oman. Oil discharged from both anchored and moving vessels can be observed in each image. Fresh slicks formed just before observations are discriminated as bright areas and relatively old thinly spread oil films are shown in dark. Based on the size of the image pixel, most of the vessels are super tankers with hull length more than 300 m.

Fujairah Port Authority has introduced Fujairah Offshore Anchorage Area (FOAA) since February 1993 to restrict and prohibit anchoring in the area from Bidiya (north of Khor Fakkan) to Dibba. Figure 8 demonstrates aspects of long-term oil contamination on beaches even though oil clean-up scheme were applied immediately after the accident. This accident occurred on 30 March 1994, when 2 super tankers, UAE tanker BAYUNA and the Panamian-registered SEKI, collided 17 km off the coast of Fujairah. Several thousand gallons of crude oil washed ashore on beaches between Khor Fakkan and Dibba in the Emirate of Fujairah. Roughly 16,000 tons of crude oil spilled into the sea, spreading over a total of 40 nautical sq. miles. Field observations in February 2003 (figure 8) show remnants of weathered oil materials nine years later. Relating these remnants to the 1994 accident has also been confirmed by testimonies of local populations as well as by the coast guard forces in the area.

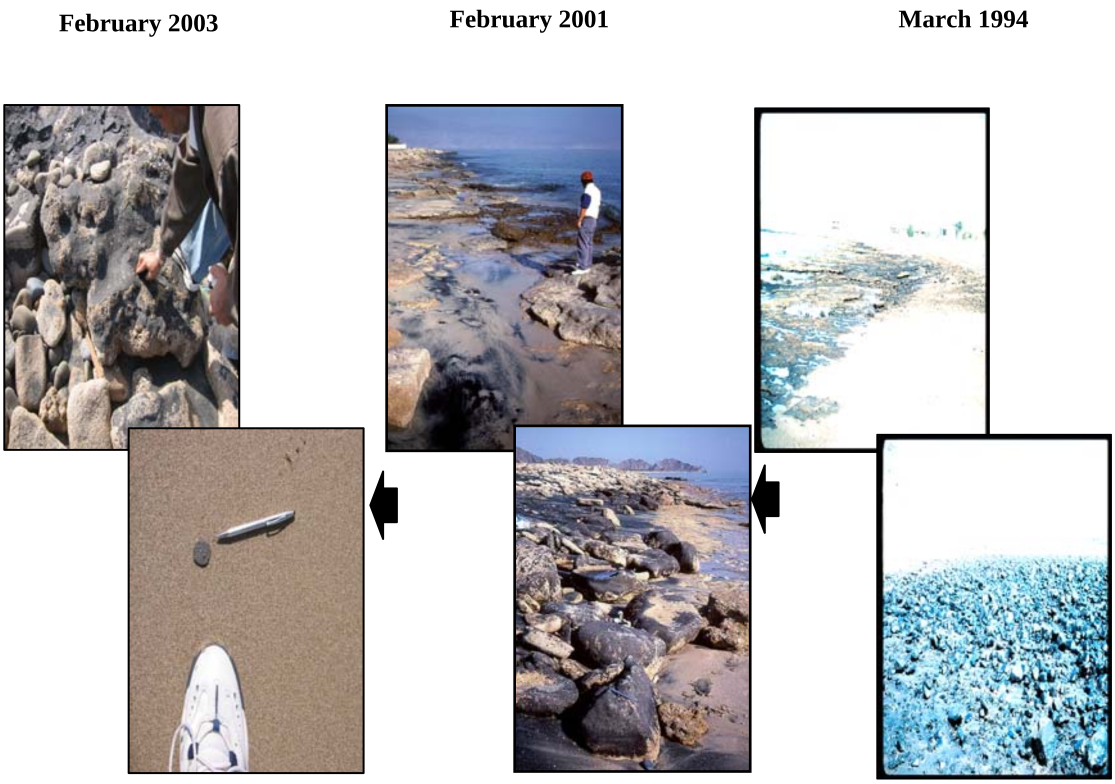

Figure 8: Oil contamination remained at the beach near Khor Fakkan although oil clean-up was carried out immediately after the incident.

3.3.2. Case 2: Coasts of Abu Dhabi, Dubai, Sharjah, Ajman, and the Strait of Hormuz

Shipping routes bordering the UAE with relatively frequent incidences of oil spills include the offshore area running parallel to the coast of Abu Dhabi, Dubai, Sharjah and Ajman, where intensive oil production activities exist, and the routes through the Strait of Hormuz. Attention was focused on monitoring leaking oil from oil production facilities in the area near to Mubarak oil field. The analysis was carried out using images from ERS-2 SAR, and ENVISAT ASAR images. Figure 9 shows leaking oil from oil production facilities (circle) offshore UAE.

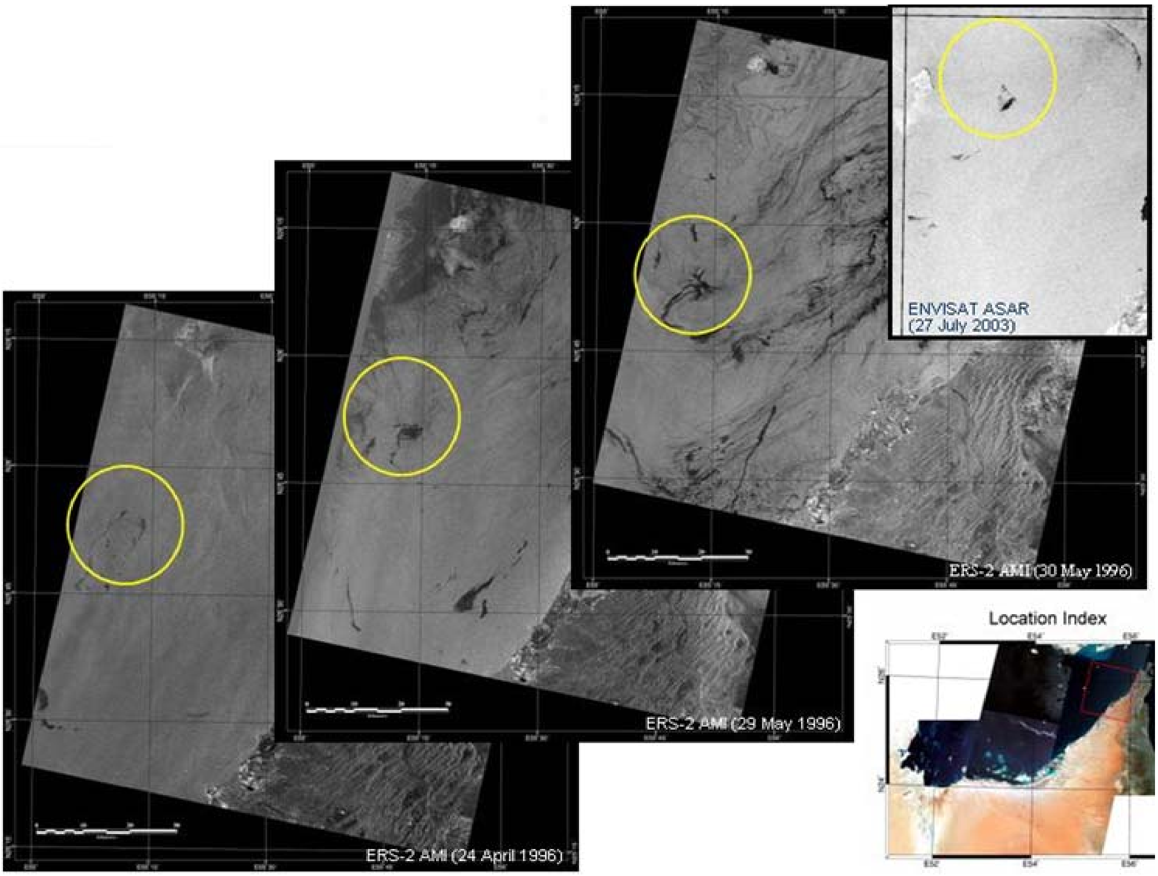

Figure 9: Multitemporal SAR (ERS and ENVISAT ASAR) image of leaking oil from oil production facilities (circle) offshore UAE.

A partial problem is the effect of extensive dark, low wind areas across the northeastern parts of the 29th and 30th May images. This weather pattern is not uncommon in the Arabian Gulf region. Scattered oil spills are marked by dark patches with a variety of sizes and shapes on the sea surface. Despite these localized problems, both images were acquired under generally acceptable conditions for slick detection. It is seen clearly that there are two polluted regions, one on the west side of the image and one in the southwest corner of the image. By overlaying this image on a map representing the oil fields and the shipping routes, a close relationship between spills, oil fields and shipping routes is found visually.

Adjacent to the oil field offshore Ras al Khaimah, near the left edge of the image (figure 9), many distinct slicks appear with different shapes, derived from oil leaking from oil production facilities. Observed slicks in the 3 images acquired on different dates are confirmed as leakage oil slicks from the same oil production platforms. In addition, locations of existing wells correspond to locations of the leakage points. The clear discrimination of these slicks on the images provides strong evidence that imaging conditions were well within the bounds for reliable oil slick detection.

4 Significance of the Study

The significance of the study can be summarized as follows:

- Technology transfer: This is the first time that a team of both international and local experts have worked together, examined and analyzed hundreds of different high resolution satellite imageries with different sensors and covering large areas to monitor oil spills in the Arabian Gulf, a very sensitive area influencing the world economy and stability.
- Awareness: raising the awareness about danger of this crucial problem was achieved and expressed by the adoption of new measures and regulations and law enforcement by various national organizations and NGOs including UAE Coastguard and the Environmental Agency of Abu Dhabi (EAD) to monitor UAE long coastlines.
- Funds: the UAE University has allocated more resources to our remote sensing lab and is now considering the funding of the production of the first UAE space oil spills Atlas, a major output of this study, reflecting positive response and significant impacts of the results of our study on local society and the country.

5 Conclusions and recommendations

Currently more than half of the oil slicks detected during this study were caused by deliberate oil discharged from moving vessels. Results confirm that the offshore UAE faces frequent occurrences of oil spills both in the Arabian Gulf and the Gulf of Oman. Shipping routes bordering the UAE with relatively frequent incidences of oil spills include the offshore area running parallel to the coast of Abu Dhabi, Dubai, Sharjah and Ajman, where intensive oil production activities exist, and the routes through the Strait of Hormuz. The analysis showed numerous small oil slicks caused by natural seeps from the seafloor. Visual overlay analysis revealed a close relationship between spills, oil fields and shipping routes.

An investigation of the causes and consequences of oil spills in the UAE waters unveiled the fact that there were not enough regulations in the UAE to deal with oil pollution. Another element was related to the limited technical ability of those, in the area, responsible for dealing with the consequences of oil spills accidents.

Furthermore, the output from this analysis proves the advantage of using satellite-borne sensors to detect and monitor oil spills in the Arabian Gulf. However, dark signatures attributed to low winds in radar images are very frequent, especially in coastal regions. Very often a whole scene or a large portion of it is under low wind conditions, which make oil slicks totally invisible. Sometimes strong wind conditions also make oil spills undetectable because they are dispersed by the surface waves and disappear below the sea surface. Use of effective sea surface, exclusive of both low and high wind areas, is a necessity for any future work. The resulting outputs have confirmed that oil spills can be detected under certain conditions. Detection capabilities of ERS, RADARSAT and ENVISAT SAR satellites are good for thin pollutants (<1µ m) and for wind speeds of 3-5 m/s. Thick emulsions can still be detected at higher wind speeds; however more investigation is needed to delimit a threshold.

Future work is needed to continue addressing this crucial problem for the Gulf States; however any effort taken in this regard should be collective, coordinated and based on new approaches including integrated environmental databases. Following are suggested recommendations for any future work to improve monitoring and detection of oil spills in the Arabian Gulf:

- Formation and continuous training of people concerned with oil spills accidents.
- Establishment of main harbours in the Gulf to make delivery of ballast water from coming ships rather than discharging this water directly into the sea.
- Complete wind speeds records (at least every 6 hours) should be made available to the remote sensing community for accurate monitoring of oil spills in the Gulf.
- Use of new generation, near-real time satellite systems with the possibility to produce time-series imageries to monitor oil spills in near-real time.
- The establishment of regional integrated GIS approaches with powerful databases containing satellite and ancillary data about the gulf area, to be able to use numerical models to predict oil spill movement in time for early warning operations.

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