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Spatial Analysis of Oil Spill Using Sentinel-1A SAR in Bintan Waters, Kepulauan Riau Province

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ABSTRACT :

Bintan Waters, located along an international maritime trade route, experiences high ship traffic, making it vulnerable to oil spill contamination. This study aims to estimate the spatial extent and volume of oil spills, categorized by oil types, using Sentinel-1 SAR data processed with the open-source software SNAP (Sentinel Application Platform). Sentinel-1 SAR data processing with SNAP software identified oil spills in multiple grids. The spills were categorized based on dB values into diesel (-15 to -20), light crude (-20 to -25), and medium crude (-25 to -30). An oil spill detected on March 23, 2023, covered an estimated area of 21.886 km². Classification of oil types was performed based on pixel profile values from the SAR imagery. The diesel-type oil spill covered 0.965 km², while the light crude type extended over 20.921 km². The medium crude type was minimal, covering 17×10^{-7} km². These oil spills pose significant risks to aquatic ecosystems, potentially harming marine life, and disrupting tourism activities. The findings provide valuable insights into the spatial patterns and dynamics of oil spills in Bintan Waters. These results can support effective monitoring, mitigation, and management strategies for marine pollution, particularly in regions with heavy shipping activity. This study emphasizes the need for proactive measures to protect marine ecosystems from oil spill impacts.

Keywords: Oil Spill, SAR, Spatial Analysis, Marine Pollution

1. Introduction :

Marine pollution, particularly oil spills, poses a significant threat to ocean health, biodiversity, and coastal communities. Oil spills involve the release of crude oil or refined petroleum products, which contain a complex mixture of hydrocarbons, including toxic substances like polycyclic aromatic hydrocarbons (PAHs) and heavy metals. These materials can spread rapidly across marine environments, coating surfaces, disrupting ecosystems, and accumulating in the food chain, leading to long-term environmental and economic damage.

Bintan Waters, located in the Kepulauan Riau Province, is especially vulnerable to oil spills due to its proximity to Archipelagic Sea Lane (ASL), a critical maritime corridor linking the Indian and Pacific Oceans. High shipping traffic in this region increases the risk of accidental spills and illegal discharges, posing significant challenges to marine conservation and resource management. Bintan Waters is a water area directly adjacent to Singapore and Malaysia. This area is located in Archipelagic Sea Lane; sea lanes established under the international conventions on the law of sea. Archipelagic Sea Lane is being made to connect two open waters, Pacific Ocean and Indian Ocean [1]. In general, ASL is categorized into ASL I, ASL II, and ASL III. The Bintan Waters is categorized into ASL I, which includes sea lanes of Java Sea, Karimata Strait, Natuna Sea, and South China Sea. This channel connects international water trade from Africa, Western of Australia to the South China Sea, and vice versa [2].

As a waterway and international trade route, the northern water of Bintan Island is always busy and have high ship mobility. The use of the sea as a waterway and international trade route can risk contamination of the aquatic environment, especially the risk of oil spills. The risk of oil spills can come from tankers, merchant ships and passenger ships [3]. The oil spill has a potential to damage aquatic ecosystems, disrupt biota life, disrupt tourism activities, and can even damage fishing boat nets. Therefore, in the case of an oil spill, it is necessary to study the predictive pattern of the distribution of oil spills in order to get the right countermeasures.

Accurate detection, monitoring, and quantification of oil spills are essential for effective response and mitigation efforts. Synthetic Aperture Radar (SAR) technology, particularly Sentinel-1A, has proven to be a reliable tool for oil spill analysis, offering capabilities to detect oil slicks under various weather conditions. Beyond spatial mapping, understanding the extent and impact of oil spills requires estimating both the wide area affected and the volume of spilled oil. Such estimations are crucial for assessing the severity of incidents and guiding appropriate remediation measures. Oil spills in the sea can be detected through remote sensing using radar; Sentinel-1 SAR (Synthetic Aperture Radar). It is important to monitor the oil spill in the northern water of Bintan Island. This is because these waters are areas with cases of oil spills that occur every year [4]. Therefore, it is important to detected oil spill in this area.

This study utilizes Sentinel-1A SAR data to conduct a spatial analysis of oil spills in Bintan Waters, focusing on the distribution patterns, potential sources, and the estimation of their wide area. By integrating advanced geospatial techniques with the strategic context of Archipelagic Sea Lane I, this research contributes to enhancing marine pollution management and conservation strategies in the Kepulauan Riau Province.

Nomenclature

Sentinel-1A : A radar satellite from the European Space Agency's (ESA) Copernicus program, designed for Earth observation
SAR (Synthetic Aperture Radar) : A satellite-based radar technology used to capture Earth's surface imagery, including detecting oil spills in marine environments
db (Decibel) : A logarithmic unit used to represent the intensity of radar signals in SAR imagery
Backscatter : Radar signals reflected from Earth's or sea surfaces, analyzed to identify specific features.

2. Materials and Method :

2.1. Study Area

The study is located in Bintan Waters, Kepulauan Riau Province, an area strategically situated along Archipelagic Sea Lanes of Indonesia I. Northern water of Bintan Island has a high potential for being polluted by oil spill. It is because of high mobility of ships. Oil spill can occur from illegal spill from ships, leakage oil pipes, and many more. The oil spill has a potential for harming aquatic ecosystems, disrupting life of biota, and can even disrupting tourism activities. Therefore, in the case of an oil spill, it is necessary to detect the wide area and volume of oil spill. Oil spills in the sea can be detected through remote sensing using radar; Sentinel-1A SAR (Synthetic Aperture Radar). It is important to monitor the oil spill in the northern water of Bintan Island. This is because these waters are areas with cases of oil spills that occur every year [4]. This region experiences high maritime activity, making it susceptible to oil spills and their associated environmental risks (Fig. 1).

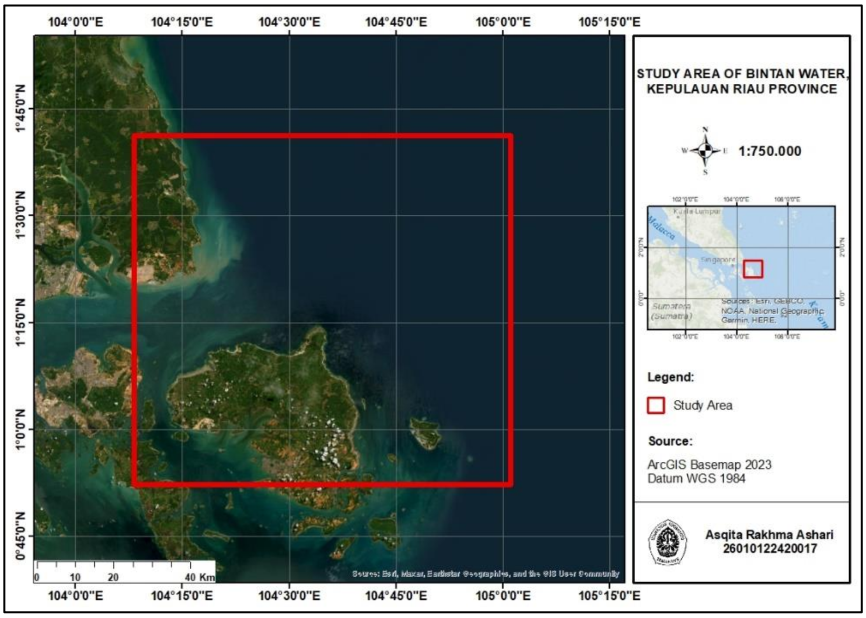

Fig. 1. Map of the Study Area

2.2. Data

The primary dataset used in this research is Sentinel-1A Synthetic Aperture Radar (SAR) imagery, captured on 23 March 2023. Sentinel-1A SAR, developed by the European Space Agency (ESA), is well-suited for oil spill detection due to its high-resolution data, ability to operate in all weather conditions, and sensitivity to surface roughness changes.

The data of this study is a Sentinel-1A SAR obtained from Copernicus Open Access Browser (https://dataspace.copernicus.eu/). Radar Image or SAR is a typical satellite imagery used to detect oil spill. It can operate in day and night. Sentinel-1A can penetrate clouds and can operate in any weather. Sentinel-1A SAR image data was first geometrically corrected to the World Geodetic System, namely WGS 1984 [5]. The Sentinel-1A SAR data used in this study is a dual-polarization image data with specifications VV (vertical transmit and vertical receive) and VH (vertical transmit and horizontal receive) Level-1 Ground Range Detected (GRD).

2.3. Oil Spill Analysis

Oil spill is detected by Sentinel-1A SAR. There are some stages in oil spill detection which include spatial subset view, calibration, geometric correction, and filtering. The result of filtering stages will analyze with adaptive threshold method in SNAP software. This method processed dark objects, which are an indication of an oil spill, using the Oil Spill Detection Tool. Dark object or dark spot in this method is a pixel with a value lower than the threshold.

The data of this study is chosen by screening high potential dark-spot from Sentinel-1A SAR images. This data represent March 23, 2023, was processed using software SNAP. If the maximum intensity value is below the average and a predetermined standard deviation, it can be used to set an adaptive threshold. This limit is used to avoid oil spill detection errors (false negative). After that, it would be tested by a negative exponential function and a quartic function below:

$$Y = -6.3041 \times 106X_4 + 0.0007327X_3 - 0.029919X_2 + 0.50015X - 2.6381 \quad (1)$$
$$Y = 7.4199e - 0.18212X \quad (2)$$

Where:
X is the value of the original pixel
Y is the value of the dark pixel [6]

The value of dark pixel would be represented to the oil spill object. Oil spill can be detected by analyzing the dark spot. It would have lower value pixel comparing to the normal water. There are some types of oil spill which could be identified by analyzing the range of plot value or decibel (db) of the dark spot. This classification represented the thickness of oil spill [7]. This oil spill classification could be determined by analyzing the db (Table 1).

Table 1. Classification of Oil Spill (Sun *et al.*,2016)

Oil Type	Plot Value (db)	Thickness (μm)
Diesel	-15-(-20)	≤ 50
Light Crude Oil	-20-(-25)	50-200
Medium Crude Oil	-25-(-30)	200-1000

3. Result and Discussion :

Sentinel-1A SAR image data was downloaded from Copernicus Open Access Browser. The data was an image recorded on March 23, 2023 at 12.00 P.M (local time). From the data, it showed that there were dark object spotted in the water. Dark object in sea surface could be suspected as oil spill. It is because the surface of oil spill cannot scattered the sensor from radar. Therefore, it reflected into backscatter object with dark appearance. SAR data is commonly used to monitor oil spills at sea where the microwave beam is emitted by the sensor and the received signal is reflected into the backscatter object features [10].

There were some dark objects spotted in this study. But, not every dark object in the sea was an oil spill. It needs to determine by analyzing the threshold from plot value (db). The value of db could be discovered from processing in SNAP software. There were some steps; cropping image data (subset), speckle filtering data, radiometric correction (calibration), geometric correction, and threshold shifting. In this study, the plot value of dark area spotted in the range of -15 – (-30) db. Based on profile plot, the dark object in sea surface has lower db than other surface. It is because the silk of oil. Detecting oil spill with SAR image relies on the fact that the oil film decreases backscattering of the sea surface resulting dark spot contrasting the brightness of spill-free area [11]. Detected oil spill is marked in red (Fig. 2).

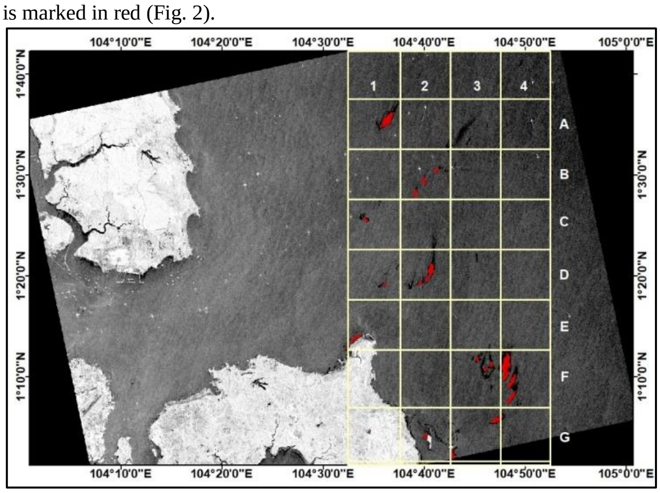

Fig. 2. Oil Spill Detected after data processing of Sentinel-1A SAR Using SNAP

The image data of Sentinel-1A SAR for March 23, 2023 had resulted to image indicated with oil spill. This result represents for temporal and spatial of oil spill in area of Bintan Waters. In general, oil spill area would have lower pixel and looks darker than the other are in the ocean or non-oil spill area (Figure. 2). Several processes in oil spill detection gives result of plot value (db) of the study area. There are some dark spot detected in the northern water of Bintan Island by SNAP software. The plot value of dark area spotted in the range of -19.9 – (-26.6) db, with the majority is between the range of -20.0 – (-23.5). The pixel profiling of oil slick could be figured out by SNAP. The result of plot value is different for each spot. In this study, the dark spot is classified into 10 area. This method is used to have an easy observation. (Figure. 3 to Figure. 12).

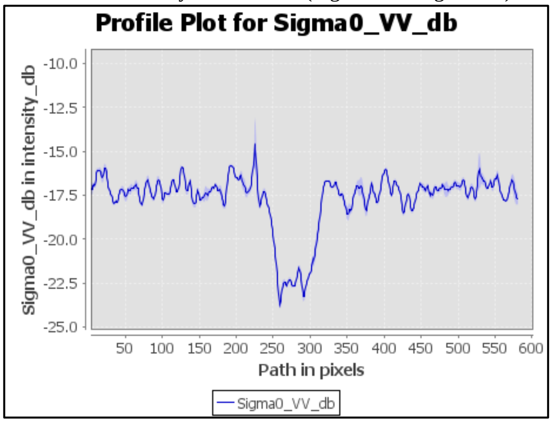

Fig. 3. Sentinel-1A Profile Value in 4F

After the process of oil spill detection, the result is only the area of oil spill. Oil spill detected in this study was colored red to clarify the location. The result of oil spill exported from SNAP with GEOTIFF format. It could be process for calculated the wide area and the volume of oil spill. Wide area calculation of oil spill is processed in QGIS software. There were some steps; convert raster pixels to polygons, extract by expression, dissolve, and the equation to estimating the wide area.

Based on the analysis of plot value, the wide of oil spill area could be estimated. The process of this estimation is using QGIS software. The results from SNAP software were exported as a GEOTIFF format images and continue the process in QGIS. There are some stages in oil spill wide area analysis using QGIS which include convert raster pixels to polygons, extract by expression, dissolve, and the equation to estimating the wide area. The estimated wide area of oil spill spotted in northern water of Bintan Island on March 23, 2023 is 21.886 km² (Figure. 13).

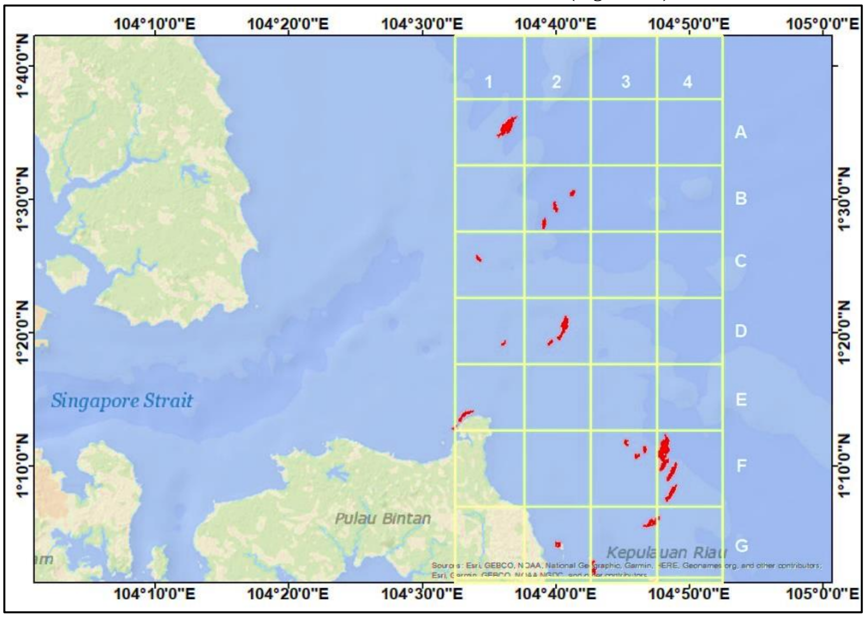

Fig. 13. Area of Oil Spill

The image data of Sentinel-1A SAR for March 23, 2023 had resulted to image indicated with oil spill. The classification of oil types could be determined by the value of db. This value could determine the type oil spill and estimated their thickness. The result of calculation wide are in this study can be classified by 3 types of oil; diesel, light crude oil, and medium crude oil.

Based on the classification of oil spill by analyzing the plot value, there are different types of oil spill spotted. Wide area of oil spill is used km^2 as a unit area. The wide area of this study is 21.886 km^2. It contains diesel, light crude, and medium crude. This classification helps determined the wide area for each types. The type of diesel were spotted with wide area of 0.965 km, the type of light crude oil were spotted with wide area of 20.921 km^2, and the type of medium crude oil were spotted with wide area of $17x10^{-7}$ km^2.

This total were a combinations of different types of oil spill; diesel, light crude, and medium crude (Table 2).

Table 2. Wide Area of Oil Spill

Oil Type	**Plot Value (db)**	**Wide Area (km^2)**
Diesel	-15-(-20)	0.965
Light Crude Oil	-20-(-25)	20.921
Medium Crude Oil	-25-(-30)	$17x10^{-7}$

The results of volume calculation for oil spill could be determined as diesel type, light crude oil type, and medium crude oil type. These types of oil spill scattered in surface water; the detected area of diesel type (Figure. 14), area of light crude oil type (Figure. 15), and area of medium crude oil type (Figure. 16).

The volume of oil spill could be calculated from wide area detected (km^2) and oil type. The wide area was processed from QGIS, and the oil type category was determined from plot value (db). The smaller value indicates the thicker layer of oil spill in seawater [8]. The thicker layer of oil spill was assumed to be the thicker viscosity of oil spill, which classified as a medium crude oil. The less thick layer of oil spill was assumed to be the lower viscosity of oil spill, which classified as a diesel. Meanwhile, the layer between the value of medium crude oil and diesel was assumed to be the light crude oil. Refer to American Petroleum Institute (API), the diesel has the gravity value more than 40, the light crude oil has the gravity value of 30 – 39.9, and the medium crude oil has the gravity value of 22 – 29.9 [9].

The result of wide area and volume of oil spill indicates that northern water of Bintan Island was polluted by oil spill on March 23, 2023. The existence of oil spill could disrupt marine lives. A marine coastal ecosystem is a marine ecosystem where the land meets the ocean. This area has an important role for biodiversity. This area has a risk on oil spill trajectory. Oil spill can disturb the ecosystem because it has toxic particles. Therefore, this incident can be prevented by predicted oil spill. There are some biodiversity in Northern waters of Bintan Island which include fish, clams, seaweed, coral reef, seagrass, mangrove, and marine mammals (Dugong dugon) [4].

4. Conclusion :

Spatial mapping of Sentinel-1As SAR could be used to oil spill detection. In this study, there were detected oil spill in Bintan Waters on March 23, 2023 at 12.00 P.M (local time). Oil spill could be determined from dark object or dark spot in sea surface. Based on data processing, there were oil spill spotted with the wide area of 20.921 km^2. The area contains different types of oil spill. The types of oil spill could be classified as diesel; with range dB of -15 – (-20), light crude oil; with range dB of -20 – (-25), and medium crude oil; with range dB of -25 – (-30). Oil spill with the diesel type was estimated 0,965 km^2 wide, the light crude type was estimated 20,921 km^2, and the medium crude type was estimated $17x10^{-7}$ km^2 wide. The result of wide area and volume of oil spill indicates that Bintan Waters was polluted by oil spill on March 23, 2023. The existence of oil spill could disrupt marine lives.

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