Spatial Distribution Characteristics of Oil Spills in the Bohai Sea Based on Satellite Remote Sensing and GIS

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ABSTRACT

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In recent years, on account of the vast and persistent damage of oil spill accidents, it becomes essential to carry out a further study on oil spill distribution characteristics on sea. Routine satellite remote sensing surveillance on oil spills with Synthetic Aperture Radar (SAR) proved to be ideal for analyzing distribution of oil pollution in macro scale. In this research work, considering the presence of "look-alikes" phenomena on SAR images as well as current operational application of "confidence level", a confidence-oriented oil spill geodatabase is initially designed and built for quantification analysis. Then, in view of the requirement of marine grid management, a common framework based on remote sensing and Geographic Information System (GIS) is proposed to map and reveal the spatial distribution of oil pollution, in the process of which, oil pollution index (OPI) is put forward to evaluate oil pollution levels, then oil pollution distribution map can be compiled in terms of OPI, and the relationship between oil pollution and oil spill risk source can be further analyzed. Finally, a case study of the Bohai Sea and the north of the Yellow Sea with five-year’s inter-annual satellite monitoring data was studied. The results showed that, during the period between 2009 and 2013, the high frequency grids of potential oil spills mainly distributed in the Bohai Bay and the south of the Liaodong Bay. 77.03 % of detected oil spills were within a certain distance along the sea lanes or near the offshore platforms, indicating a high risk of oil pollution of these areas. Generally, this research work also benefits for yield for the first time a rather comprehensive distribution characteristics of potential oil spills in macro scale in the Bohai Sea combined with remote sensing and GIS technique, which will be beneficial for oil spill response, preparedness and risk management.

ADDITIONAL INDEX WORDS: Oil spill, oil pollution index (OPI), satellite remote sensing, spatial distribution characteristics, the Bohai Sea.

INTRODUCTION

Oil spill is considered as one of major threats to marine ecosystem. Since the early 1970s, International Maritime Organization (IMO) has been working to prevent this kind of pollution in the framework of MARPOL73/78, which in Annex I deals specifically with prevention of oil pollution (Martínez and Moreno, 1996). In recent years, huge oil spills still occurred irregularly, such as Deepwater Horizon (DWH) spill in the Gulf of Mexico, the Dalian 7.16 oil pollution accident in China. Both the public and the local government have a focus on oil spill risk analysis and preparedness. Meanwhile, it becomes essential to carry out further study on the characteristics and laws of oil pollution at sea, which will directly benefit for oil pollution emergency preparedness.

Satellite remote sensing has been extensively used to detect oil spills on sea surface (Brekke and Solberg, 2005; Fingas and Brown, 1997; Keydel and Alpers, 1987; Xing et al., 2015; Zhang et al., 2016). Passive optical remote sensing of oil spills using sunlight has been used for several decades, and significant progress in oil spill detection, classification, and quantification based on different optical properties and algorithms have been made in recent years (Lu et al., 2016; Su et al., 2012). Laser induced fluorescence technique has also been used for the detection of marine oil spills (Luan et al., 2017). During the vast and persistent BP deepwater horizon oil spill accident in 2012, extensive airborne and spaceborne passive and active remote sensing were used to monitor oil spills and provide rapid response (Leifer et al., 2012). In practical application, oil spill can be detected more effectively by Synthetic Aperture Radar (SAR) images because it damps short surface waves and thus reduces the backscattered radar power over these areas. As a result, SAR is more widely used for oil spill monitoring in application. A detailed state-of-the-art for oil spill detection methodology using SAR imagery is discussed by a number of scientists including Ferraro et al. (2012), Liu et al. (2011), Martínez and Moreno (1996), Solberg et al. (2007), and Topouzelis et al. (2007). It is very valuable for decision-makers to understand the characteristics of oil spills, which will directly benefit for oil spill emergency preparedness. Garcia et al. (2013)
developed an Oil Spill Hazard Index (OSHI) to evaluate the pollution risk level along the whole Italian coastline and waters. Liu et al. (2015) utilized satellite images together with historic accident data to establish probability of oil spills to assess oil spill risks. Yu et al. (2018) showed that oil spill risk assessment in the Chinese Bohai Sea becomes more important for efficient prevention. Some successful experiments and projects have been carried out to monitor oil spills via space-borne SAR images and study its distribution characteristics through big data. For instance, Pavlakis, Tarchi, and Sieber (1996) interpreted 190 ERS-1 SAR images to analyze oil spill distribution in the Mediterranean. More than 660 ERS-2 SAR images covering the southern Baltic Sea, the North Sea, and the Gulf of Lion were analyzed within the “Clean Seas” project, which was funded by the European Community (EC), aiming at investigating the application of remote sensing for oil spill detection and coastal management (Gade et al., 1998). With the rapid development of Geographic Information System (GIS), it provided a useful tool for mapping and spatial analysis at large scales (Choi et al., 2011; Žímek et al., 2001). In order to get enough knowledge on spatial distribution characteristics of oil pollution on sea, oil slick information extracted from SAR images can be used to make zoning maps for oil pollution. A GIS approach to mapping marine oil pollution was applied to the Sea of Okhotsk, the Caspian Sea, the Black Sea and the Gulf of Thailand, respectively (Ivanov and Zatyalagolova, 2008). In China, based on over six thousands of ERS-1/2 SAR images acquired within the period from 1995 to 1998, Lu et al. (1999) mapped the spatial distribution of oil pollution in the Southeast Asian waters. In 2008, Shi et al. (2008) interpreted more than 600 SAR images captured from 2002 to 2005 in the western part of the East China Sea, then analyzed and mapped the spatial distribution of oil spills.

However, owing to the complexity of space-borne SAR imaging mechanism and ocean-atmosphere system, there are also a large number of “look-alikes” phenomena which can easily be mistaken as oil slicks on SAR images, e.g., some areas with low wind speed or upwelling areas can also generate dark patches, that is, oil spill detection on SAR images highly depends on individual experience to a certain extent. As a result, different labels of “confidence”, such as high level, medium level or low level, are commonly used to describe the uncertainty of interpretation results in operational application (Ferraro et al., 2010). Unfortunately, this uncertainty rarely reflected in an oil pollution distribution maps. At the same time, China Maritime Safety Administration (MSA) are implementing maritime grid management in territorial waters, in which how to combine the uncertainty of oil slick detection on SAR images , spatial analysis of GIS and the requirement of maritime grid management in one oil pollution zoning map becomes an important issue.

In this research work, a confidence-oriented oil spill geodatabase storing information both extracted from SAR images and acquired from on-site investigation was designed and built initially for quantification analysis. Then, an estimation methodology for oil pollution based on confidence-oriented oil spill geodatabase and GIS was proposed, in which the oil pollution index (OPI) was proposed and calculated. Finally, a case study was carried out based on a five-year routine satellite monitoring of oil pollution in the Bohai Sea and the north of the Yellow Sea, then oil pollution maps were compiled in terms of OPI and meanwhile the spatial distribution of oil pollution was discussed in macro scale for the purpose of providing some valuable information for oil spill risk management.

Methods

Study Area

The study area is located between 117°E and 123°E, and 37°N and 41°N. It includes the Bohai Sea and the northern part of the Yellow Sea (Figure 1). In particular, as China's continental sea, the Bohai Sea plays a significant role in national economy and social development. There are three bays from north to south, including the Liaodong Bay, the Bohai Bay, and the Laizhou Bay, and also several main ports, such as the ports of Yingkou, Qinhuangdao, Tianjin, Dalian, Yantai, etc. With the increasing number of shipping business and offshore oil exploitation, the risk of oil pollution in this region is getting higher and higher. Specifically, in recent years, according to the data from Vessel Traffic Control (VTS) it showed that the number of the actual accidents in relation to the intense maritime traffic that taken place in this area increased gradually. Besides, as one of the most important areas where petroleum enriched and produced, some major oilfields, such as Jinzhou oilfield, Bohzhong oilfield, Chengbei oilfield, Penglai oilfield, etc., were located in the Bohai Sea. All of these factors lead to a high risk of oil pollution in this study area.

Data Acquisition

The Bohai Sea was chosen for the study also due to the availability of the necessary oil spill remote sensing data. During the period from January 2009 to December 2013, the China Maritime Safety Administration carried out satellite remote sensing surveillance for oil spills in the Bohai Sea and the north of the Yellow sea, acquiring copious number of oil pollution information both accidental spills and non-reported oil spills. A total of 323 SAR images were collected for oil spill monitoring, including Envisat-1 and Radarsat-1/2 (Table 1 and Table 2).

Table 1. Statistics of original SAR images.

| Data sources | 2009 | 2010 | 2011 | 2012 | 2013 | total |
|-------------|------|------|------|------|------|-------|
| Envisat-1   | 29   | 24   | 8    | 0    | 0    | 61    |
| Radarsat-1/2| 22   | 18   | 29   | 82   | 111  | 262   |
| Total of SAR images | 51   | 42   | 29   | 90   | 111  | 323   |

Table 2. Statistics and comparisons of potential oil spills detected from SAR images.

|                  | 2009 | 2010 | 2011 | 2012 | 2013 | total |
|------------------|------|------|------|------|------|-------|
| Potential oil spills Images covering oil spills | 43   | 51   | 33   | 26   | 56   | 209   |
| Original SAR images | 11   | 10   | 11   | 14   | 20   | 66    |
| Occurrence rate | 21.6 % | 23.8 % | 37.9 % | 15.6 % | 18.0 % | 20.4 % |
The spatial resolution of these data was from 8 m to 30 m, mainly by VV polarization. In addition, auxiliary data, such as wind velocity, electronic nautical chart, AIS marine traffic data, offshore platform data, etc., were also used for aid analysis and oil spill detection. The software PCI 10.3 was used for image processing, and ArcGIS 10.0 and Matlab for data analysis.

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Methodology

Three steps were conducted in this study: (a) building a confidence-oriented oil spill geodatabase; (b) creating a net grid covering the study area, establishing and calculating oil pollution index (OPI) for each grid cell to evaluate oil pollution level; (c) generating oil spill distribution map base on OPI and analyzing spatial characteristic with GIS, as described below.

Confidence-oriented Oil Spill Geodatabase

As mentioned above, different labels of “confidence” are commonly used to describe to what extent a potential oil slick detected from SAR images to be a real one. But descriptions such as high level, medium level or low level are not suited for quantitative calculation. So, “confidence index” is designed to transfer qualitative evaluation to quantitative calculation.

As is shown in Table 3, confidence index with the numerical value ranging from 0 to 1 is defined to measure the probability of a potential oil slick on SAR images to be a real one. For example, if the confidence index of a potential oil slick is 0.9, it indicates that the probability of this potential oil slick to be a real one is very high, almost between 80 % to 100 %, and it will be classified as category II. Confidence index of each potential oil slick can be determined by two steps:

a) Calculating preliminary confidence index using the Analytic Hierarchy Process (AHP) and the expert scoring method (Dey, Ogunlana, and Naksuksakul, 2004). That is, in this process, each potential oil slick on SAR images will be interpreted by at least 7 experts and marked independently in the light of the probability of being a real one. Then AHP is applied to determine the preliminary confidence index.

b) Determining final confidence index based on on-site verification. In general, if conditions permit, patrol ships or aircrafts will be sent to check the potential oil slick as soon as it is interpreted from SAR images, then the final confidence index will be corrected according to the results of on-site investigations. For instance, if the preliminary confidence index of a potential oil slick is calculated to be 0.9 in the first step, after on-site verification in the second step, it is confirmed as a real oil slick, the final confidence index will therefore be revised to 1 (Figure 2). Of course, not every oil slick detected from remote sensing images can be checked by on-site verification. In this case, the final confidence index will be in accordance with the preliminary confidence index.

With the item of “confidence index”, a confidence-oriented oil pollution geodatabase is therefore built, some other information is also stored and managed in this database, including geographic position of oil slicks, vector shape, lengths and area of oil slicks, acquiring date and time of SAR images, etc. Each oil slick item is supposed to be stored as a single vector layer.

Oil Pollution Index (OPI)

In this section, a regular net grid covering the study area will be firstly established in accordance with both the needs of marine grid management and the basic state of oil spills in this region. The whole study area is therefore divided into 5263 grids with the scale of 5 × 5 km.

Figure 2. Examples of determining confidence index of potential oil slicks on SAR images: (a) Radarsat-2 image; (b) oil spills and look-alikes detected from the image; the confidence index of the top right potential oil slick is 1 (marked with yellow line), the confidence index of the bottom right potential oil slick is 0 (marked with green line); (c) optical photos of oil spills validated by aerial remote sensing monitoring (helicopter).
In this paper, oil spill frequency is selected as the key attribute value for the spatial distribution characteristics of oil spills in the Bohai Sea. Satellite remote sensing and GIS are used to analyze the data and generate an oil pollution index (OPI) map for each grid cell. The probability of oil spill risk during the study period is calculated using the total number of images counted in the area size of 1 to 10 km$^2$ for oil spills from 2009 to 2013. The area size of oil spills has been detected from Radarsat-1/2 and Envisat images. The oil pollution index (OPI) parameter is not absolute but relative, and the outcome can be used to compare the relative probability of the whole area affected by oil spills. The area size of oil spills has been detected from Radarsat-1/2 and Envisat images.

Table 3. Classification of oil pollution confidence index.

| Category | Probability for oil pollution | Confidence index | Description |
|----------|-------------------------------|------------------|-------------|
| I        | 100%                          | 1                | Oil slicks checked by facts |
| II       | 80%≤p<100%                    | 0.9              | Very high confidence level |
| III      | 60%≤p<80%                     | 0.7              | High confidence level |
| IV       | 40%≤p<60%                     | 0.5              | Medium confidence level |
| V        | 20%≤p<40%                     | 0.3              | Low confidence level |
| VI       | 0%≤p<20%                      | 0.1              | Very low confidence level |
| VII      | 0%                            | 0                | Look-alikes |

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RESULTS

Statistical Analysis

In the case study, as mentioned above, the results presented here concern mainly on non-reported oil spills detected from routine satellite remote sensing of the Bohai Sea and the north of the Yellow Sea. A total of 323 SAR images over 5 years since 2009 are used to investigate oil spill distribution, the majority of which is from Radarsat-1/2 and Envisat-1. After interpreting these images, 209 potential oil slicks have been detected from 66 images (sometimes more than one oil slick in an individual SAR image), accounting for 20.43% of the total 323 images studied, that is to say, oil slicks can be found in one image out of five during the period between 2009 and 2013. In addition to the number of oil spills, another important factor to reflect the risk level of oil pollution is the area size of oil slicks which can be extracted from SAR images as well. As it appears in Figure 3c, the total area of these spills is 834.63 km$^2$, and the tendency of annual area of detected spills is on the whole increasing dramatically, indicating a sharp growth of oil spill risk during the study period. The area sizes of oil spills varied from 0.01 km$^2$ to even more than 48 km$^2$, about 42.58% of the spills are less than 1 km$^2$, the number of spills between area size of 1 to 10 km$^2$ is 45.93%. This means the majority (almost 88.52%) of the total spills during the study period are less than 10 km$^2$. Monthly statistics of the whole 5 years shows that the monthly variation of average area of oil slicks is not obvious (see Figure 3d).
The spatial distribution map of potential oil spills in terms of OPI was shown in Figure 4, all the grids were divided into 4 categories by means of Natural Breaks (Michael John De Smith and Paul, 2009), obviously the frequency of oil spill was relatively high in the Bohai Bay, the south of the Liaodong Bay, the middle of the Bohai Sea, and the northwest of the Yellow Sea. The total number of grid cells with oil pollution index higher than or equals to 2 \( (OPI_{ij} \geq 2) \) was 113.

Figure 3. Histogram of statistics of potential oil slicks from January 2009 to December 2013: (a) proportion of SAR images covering potential oil slicks; (b) annual number of potential oil slicks detected from SAR images; (c) total/average area of potential oil slicks each year and (d) monthly statistics of potential oil slicks area of 5 years.

The result of oil spill spatial distribution basically agreed with a recent research that investigated regional and seasonal features of potential oil slick with satellite SAR images covering the Bohai Sea in 2011 (Ding et al., 2016). However there were some differences in oil spill temporal distribution. It was probably due to various SAR data types and different time scales of selected study samples. As the non-uniform spatial repetition density of the routine satellite SAR images of the whole study area, the results are then somehow biased towards these data.

In order to investigate the relationship between oil spills detected from SAR images and the major oil spill hazards in the waters, a further buffer analysis was carried out using GIS tools. The main sea lanes and offshore platforms of the waters are selected as oil spill hazards.

As presented in Figure 5, the main sea lanes were divided into two types (lane A and lane B) according to vessel traffic density. Based on a series of experiments, the buffer distance of offshore platforms and lane A was selected as 8 km, and that of lane B was 5 km, so that the characteristics and relationship could be reflected better and more clearly. The results were presented in Figure 6, the number of spills within the buffer distance to the two types of sea lanes was 116, representing 55.5% of all detected spills, these results were well in accordance to the study which concluded that most oil slick originate from ships (Ding et al., 2016). A connection between oil spills and ship lanes was Southeast Asian waters (Lu et al., 1999), the Mediterranean sea also obtained from some other waters in the world, like the (Pavlakis, Tarchi, and Sieber, 2001), the Azov and Black Seas (Bedritskii et al., 2007) and the East China Sea (Shi et al., 2008). In particular, the proportion of those to platforms was about 21.53%, which indicated that platform was also a major hazard causing potential oil spills in the Bohai Sea. What's more, the number of spills with the distance equaled zero was 50, that is to say, about 23.92% were more likely to be caused by the corresponding hazards. The average distance was 655.84 m, 732.03 m, and 1481.13 m between oil slicks detected and offshore platforms, lane A, lane B, respectively.

Figure 4. Spatial distribution map of potential oil spills based on OPI in the Bohai Sea and north of the Yellow Sea during the period of January 2009 to December 2013.

Figure 5. Buffer analysis of main sea routes and offshore platforms of the study waters.
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CONCLUSIONS

In this research, considering the presence of “look-alikes” phenomena on SAR images, which leads to the problem of uncertainty for potential oil spills in operational application, a confidence-oriented oil spill geodatabase was designed and built for quantification analysis. Then, an estimation methodology for oil pollution based on satellite remote sensing and GIS was proposed. During this process, the oil pollution index (OPI) was put forward and calculated. In the end, oil pollution map was compiled in terms of OPI and the spatial distribution of oil pollution was discussed.

Generally speaking, the results of the case study in the Bohai Sea and the North of the Yellow Sea showed that, during the period of 2009 to 2013, the high frequency grids of potential oil spills mainly distributed in the Bohai Bay, the south of the Liaodong Bay, the middle of the Bohai Sea, and the northwest of the Yellow Sea. 77.03% of detected oil spills were within a certain distance along the sea lanes or near the offshore platforms, indicating a high risk of oil pollution of these areas. With this information at hand, the government can give priority to these areas and seasons being prone to oil pollution when drawing up routine marine cruise and air cruise plans.

Although this research work is preliminary in the Bohai Sea, it yields for the first time a rather comprehensive spatial distribution map of potential oil spills combined with remote sensing and GIS technique, which will to some extent be beneficial for oil spill risk preparedness and management. However, for such random events as oil spills, a great deal of long-term surveillance data with SAR images is highly recommended to study the characteristics and laws of oil pollution, since the results might be improved by data mining on large amounts of statistical data better and more objectively.

AUTHOR CONTRIBUTIONS

All of these authors contributed equally to this work.

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