MULTI-TEMPORAL ASSESSMENT OF OIL SPILL FREQUENCIES, LEAK SOURCES AND THEIR CONTROLLING NATURAL FACTORS AND VALIDATION OF ACHIEVED RESULTS THROUGH THE STOCHASTIC MODELING OF OIL SPILLS IN THE CASPIAN SEA USING GIS AND REMOTE SENSING

Emil R. Bayramov(1), Manfred F. Buchroithner(1), Rafael V. Bayramov(2)

(1)Dresden University of Technology, Helmholtzstr. 10 Hülsse-Bau, Westflügel Zimmer W136,Germany, Email:emil.bayramov@yahoo.com; manfred.buchroithner@tu-dresden.de

(2)Baku State University, Inshaatchilar Avenue 31, Apt. 3, AZ1065, Baku, Azerbaijan Email: rafael_karta@mail.ru

ABSTRACT

The main goal of this research was to detect oil spills, to determine the oil spill frequency, and to approximate oil leak sources around the Oil Rocks Settlement, the Chilov and Pirallahi Islands in the Caspian Sea using multitemporal ENVISAT ASAR WSM images acquired in the period of 2009–2010. The hot spot areas of detected oil spill frequencies for 2009–2010 were the following: 2–25 (4,658.83 sq. km.), 26–45 (302.83 sq. km.), 46–75 (77.95 sq. km.). The most critical oil leak sources were observed around the Oil Rocks Settlement. The exponential regression analysis between wind speeds and oil slick areas in 2009 with R^2 equal to 0.61 showed that larger oil spill areas were observed with lower wind speeds. The spatiotemporal patterns of currents in the Caspian Sea explained the multidirectional spatial distribution of oil spills around the Oil Rocks Settlement.

1. INTRODUCTION

The Oil Rocks Settlement, Chilov and Pirallahi Islands in the Caspian Sea were selected as the study areas because of their long-term oil exploration history. Oil slicks in the Caspian Sea have different sources such as spills resulting from offshore oil installation [1], ship accidents, and illegal releases [2; 3] and other natural processes, etc. Detection of oil spills caused by anthropogenic oil exploration activities plays a significant role in the environmental management of cleaning activities and response to emergency situations.

Detection of natural seepage is considered to be one of the significant preliminary works for offshore petroleum exploration [4; 5]. The oil slick detection and mapping were often used for the hydrocarbon exploration activities and emergency response to oil spill incidents in the world places such as Gulf of Mexico [6] and South Caspian Sea [7; 8; 9; 10; 11], Australian Shelf [12], and Santa Barbara Channel, California [13]. Oil spill satellite detection was also used during the Lebanese oil spill pollution crisis [14] during the hostilities between Israel and Lebanon back in 2006, as well for routine monitoring of illegal oil slicks from maritime traffic [15]. It is well known that microwave sensors have the advantage for oil slick monitoring due to its wide area coverage and day and night capabilities [5; 16; 17; 18; 19; 20; 21]. Radar backscattering level decreases with slick and appears as a dark patch with lower backscatter from the sea surface [22]. The limitation of synthetic-aperture radar (SAR) is that it does not have capabilities for oil spill thickness estimation and oil type recognition. However, SAR is useful particularly for searching large areas and observing oceans and seas at night and at cloudy weather conditions. Possibilities for the detection of oil slicks depend on radar polarization modes, height of the waves, the amount of oil that has been released, slick nature, the speed of the wind, and type of oil [23; 24; 25; 26]. The discrimination of oil spill look-alikes from oil slicks produced by oceanic and atmospheric processes is one of the most complex issues in the process of oil slick detection from SAR images. Discrimination of oil slicks from look-alikes is performed based on the textural, geometrical, radiometric, and temporal features [4; 5; 27; 28; 29]. The main goal of this research was to study oil pollution around the Oil Rocks Settlement, Chilov and Pirallahi Islands in the Caspian Sea using ENVISAT advanced synthetic aperture radar (ASAR) wide swath medium (WSM) resolution satellite images acquired during the period of 2009–2010. The detailed research goals are following:

1. Detection of oil spill using multi-temporal SAR images around the Oil Rocks Settlement, Chilov and Pirallahi Islands in the Caspian Sea for the period of 2009–2010.
2. Multi-temporal analysis of oil spill frequency to detect spatiotemporal distribution trends in marine environment and to determine hot spots of regular oil pollution.
3. Approximation of probable oil leak source locations from the Oil Rocks Settlement, Chilov and Pirallahi Islands based on the frequency of detected oil pollution.
4. Determination of spatial relationships among detected

oil spills, wind speeds, and currents in the Caspian Sea.

The first research objective is performed for the determination of spatial distribution of oil slicks based on the individual ENVISAT WSM radar satellite image. The second research objective is performed through the overlaid segmentation of multi-temporal oil spills using the geospatial analysis to compute the oil spill frequency based on the multi-temporal ENVISAT satellite images. The third research objective is performed for the approximation of probable oil leak sources based on the detected oil spill frequency from the multi-temporal ENVISAT satellite images, and the fourth research goal is to determine the relationship between detected oil spills and natural factors as wind speeds and currents. A number of research activities were performed for the studies of oil pollution in the Caspian Sea using SAR technologies. One of the research activities for the studies of oil pollution around the Oil Rocks Settlement was performed by [7] using RADARSAT-2 satellite images. This research allowed determining the oil slicks, negative environmental situation around the Oil Rocks Island, correlation between oil spill area and wind speed, and optimal polarization mode for the detection of oil spill using RADARSAT-2 images. Another research of [8] emphasized not only the role of Geographical Information Science in the qualitative and quantitative characterization of spatial and temporal distribution of oil spills but also of the environmental conditions of the sea basins as a whole. [11] applied the ENVISAT SAR imagery for mapping and estimation of natural oil seeps in the South Caspian Sea. This research was focused on the assessment of the SAR images in the relationship with bathymetry, geophysical and seismic data and showed that the main hydrocarbon contribution visible on the Caspian Sea surface as oil slicks comes from the natural seepage.

2. STUDY AREA

The Oil Rocks Settlement, Chilov and Pirallahi Islands in the Caspian Sea were selected as the research areas because of their long-term oil exploration history. The difference is that the Oil Rocks Settlement is artificially developed one whereas Chilov and Pirallahi Islands have the natural origin. The Oil Rocks is an industrial settlement in Baku, Azerbaijan. It is located 35 km from the coast of the Caspian Sea. The Oil Rocks is a functional city with a population of about 2,000 and with a length from east to west over 300 km. The map of the Oil Rocks Settlement, Chilov and Pirallahi Islands is presented in Fig. 1. The settlement of the Oil Rocks was built in 1949 after oil was discovered there at 1100 meters beneath the Caspian Sea and it became the first offshore oil infrastructure based on the steel trestle bridges joining the man-made islands in Azerbaijan (Fig. 2a; 2b). By 1951, the Oil Rocks Settlement was ready for production with the equipped infrastructure needed at the time. In 1952, the systematic construction of trestle bridges connecting the artificial islands was begun.

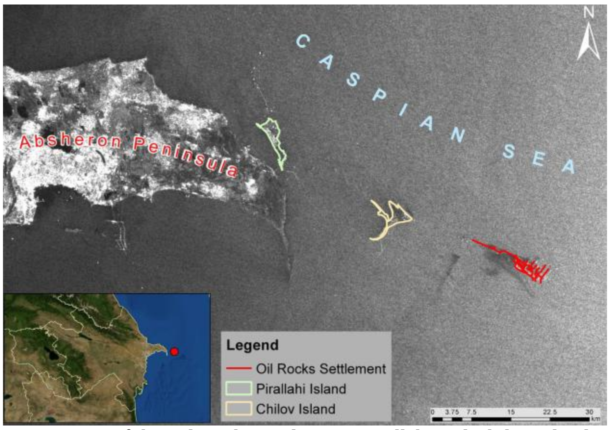

Fig. 1 Map of the Oil Rocks Settlement, Pirallahi and Chilov Islands

Fig. 2 a Picture of the Oil Rocks Settlement; b Picture of Pirallahi and Chilov Islands

3. DATA PROCESSING

ENVISAT radar satellite images were used for the purpose of oil slick detection, computation of oil spill frequency, and approximation of oil leak sources for the period of 2009–2010. On 1 March 2002 ESA's ENVISAT satellite was launched, and data from sensors like ASAR operating at C-band were available until

ENVISAT operational services finished in April 2012. ENVISAT ASAR data come in different modes with different spatial resolutions and coverage. ENVISAT data are available in image, wave, and alternating polarization modes at approximately 30 m 9 30 m in the highest resolution, approximately 150 m 9 150 m in wide swath mode (WS), and at 1 km pixel resolution in global monitoring (GMM) mode. ENVISAT ASAR WSM images were used for this research. ENVISAT ASAR WSM images have a swath width of 400 km and 150 m pixel spacing. Wide Swath Mode uses ScanSAR technique with VV (vertical transmit, vertical receive) or HH (vertical transmit, horizontal receive) polarisation. The VV polarisation mode was used for the present research because of the technical suitability for the oil spill detection. The extents of used ENVISAT images are presented in (Fig. 3a; 3b). The count of ENVISAT images in 2009 and 2010 is presented in Table 1. The appearance of oil slicks in SAR imagery depends on the Caspian Sea conditions during the acquisition, in particular the wind speed and also on the oil parameters as spill age and oil type. If the wind speed is very low then the surface might be very smooth with low level of the backscatter causing difficulties in the detection of oil spill. In case of low wind speed, it can be possible to detect thin slicks but it may be difficult to separate thick slick (Fig. 4a). Low wind areas can be misinterpreted as oil slicks. If, on the other hand, the wind speed is too high (say >14 m/s) then the surface is very rough and waves are not noticeably attenuated by the oil. Also in this case, oil is hardly visible in the SAR images in a limited way. In case of high wind speed, advantage is that thick slicks can be detected whereas it can be difficult to detect thin slicks as it is shown in Fig. 4b. The most suitable conditions are intermediate wind conditions (2.5–14 m/s) so that the oil can generally be detected by the SAR as dark areas in the imagery. That is why the images for this research were selected in accordance with the suitable weather conditions (2.5–14 m/s) for the detection of oil spill. In spite of the development of automatic and semiautomatic oil spill detection methods of SAR image analysis which also require operator supervision, visual methods of interpretation still dominate. The work flow for the detection of oil spill frequency and approximation of oil spill sources is presented in Fig. 5.

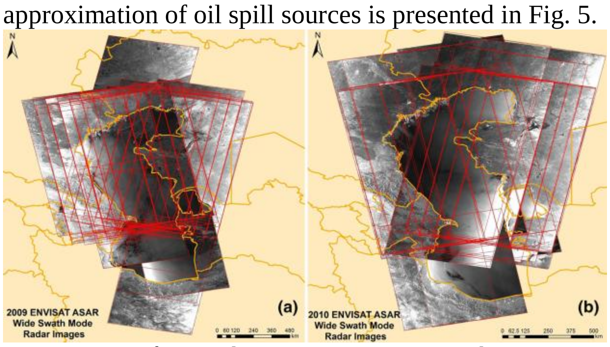

Fig. 3 Extents of acquired ENVISAT ASAR WSM radar images in: (a) 2009 and (b) 2010

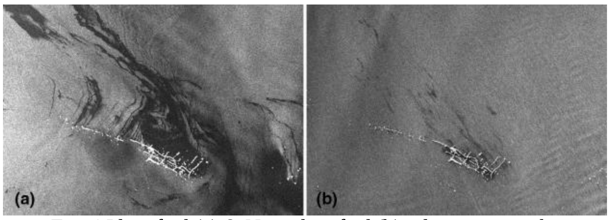

Fig. 4 Identified (a) & Non-identified (b) oil patterns on the ENVISAT ASAR WSM Images

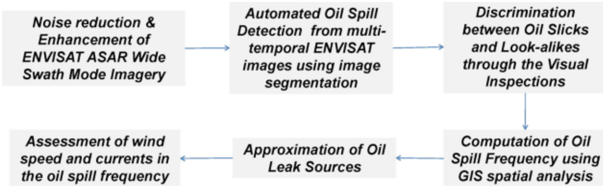

Fig. 5 Workflow for the detection of oil spill frequency and approximation of oil leak sources

Table 1 Number of ASAR WSM images acquired in 2009 and 2010

Months	Type of images	Acquired in 2009	Acquired in 2010	Wind speed	Polarisation mode
January	ASAR WSM	–	2	2.5–14 m/s	VV
February	ASAR WSM	–	–	2.5–14 m/s	VV
March	ASAR WSM	3	–	2.5–14 m/s	VV
April	ASAR WSM	–	2	2.5–14 m/s	VV
May	ASAR WSM	5	4	2.5–14 m/s	VV
June	ASAR WSM	6	6	2.5–14 m/s	VV
July	ASAR WSM	7	7	2.5–14 m/s	VV
August	ASAR WSM	5	6	2.5–14 m/s	VV
September	ASAR WSM	8	6	2.5–14 m/s	VV
October	ASAR WSM	10	3	2.5–14 m/s	VV
November	ASAR WSM	7	1	2.5–14 m/s	VV
December	ASAR WSM	–	–	2.5–14 m/s	VV
Total		51	37		

Each individual ENVISAT WSM image was enhanced and the noise removed to increase possibility of oil spill detection. Preliminary image segmentation procedure for detection of dark features was performed to contribute to the visual interpretation process. The visual interactive interpretation and classification were performed to discriminate actual oil slick from look-alikes on the basis of geometrical/textural properties and contextual information. GIS overlay analysis was performed for the segmentation of multi-temporal oil spills, computation of oil spill frequency, and determination of spatiotemporal distribution. Computed frequency of oil spills around the Oil Rocks Settlement, Chilov and Pirallahi Islands also allowed approximating oil leak source locations as a root cause. The exponential regression analysis was performed between detected oil spill areas and wind speeds to understand the role of wind in the spatiotemporal distribution of oil spill frequencies.

4. RESULTS

Detected hot spots from oil spill frequencies

The count and area of oil spill frequency in the period of 2009–2010 significantly differed from individual spill frequencies in the years 2009 and 2010 showing the continuous spill of oil around the Oil Rocks Industrial

Settlement, Chilov and Pirallahi Islands (Figs. 6-8). Since these computations are explicitly based on the available and useful images for oil spill detection, it was not possible to compare oil spill rates of 2 years. This approach allowed to detect hot spots with high frequencies of oil spill, spatial distribution, and approximated oil leak sources for the planning of cleaning activities. The detection of oil spill from 89 ENVISAT ASAR WSM images and multi-temporal overlay analysis allowed increasing the accuracy and reliability of detected oil spill and model the spill frequency by criticality level. The oil spill areas with no overlaps and far away from the oil spill sources were not presented because of the lower reliability of occurrence.

Approximated oil leak sources

The approximated oil leak sources are presented in Fig. 9. It is possible to observe that the most critical classes of oil leaks are located around the Oil Rocks Settlement. The computed frequency of large and persistent oil leaks was in the range of 61–84. The medium class of oil leak sources can mainly be observed around the Oil Rocks Settlements and Chilov Islands. Small and occasional leak sources can mainly be observed around the Chilov and Pirallahi Islands.

Relationship among wind speeds, currents, and oil spills

The major factors that shape the currents of the Caspian Sea are the impacts of the wind. The prolonged shape and topography of the seashore and seabed also exerts a substantial impact on the nature of the currents. All of these factors cause the variability in the spatial temporal changes of currents in the Caspian Sea. General speeds of the current in the Caspian Sea are 20–30 mm/sec. The greatest values of current speed, which is reaching up 100 mm/sec, are observed in an area near Apsheron peninsula, between Chilov Island and the Oil Rocks Settlement. The current first and wind second are those factors, which affect the slick size and shape. The exponential regression analysis between wind speeds and oil slick areas in 2009 with R^2 equal to 0.61 showed that larger oil spill areas were observed with lower wind speeds (Fig. 10). Wind speed is one of the controlling factors of spatiotemporal changes of oil slick areas around the Oil Rocks Settlement, Chilov and Pirallahi Islands. The Caspian Sea currents have the dynamic multi-directional patterns and speed which explain spatial distribution of oil spills in various directions around the Oil Rocks Settlement.

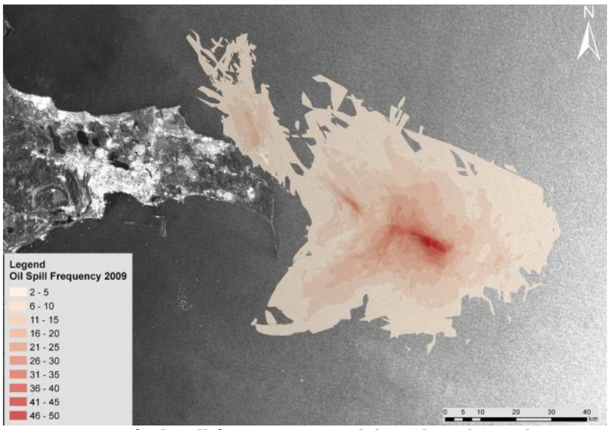

Fig. 6 Map of oil spill frequency around the Oil Rocks Settlement, Chilov and Pirallahi Islands in 2009

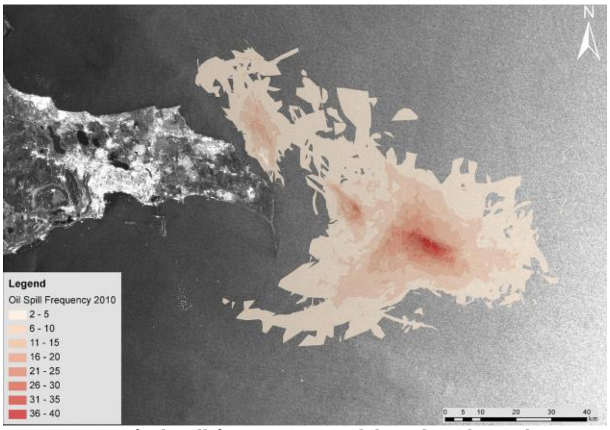

Fig. 7 Map of oil spill frequency around the Oil Rocks Settlement, Chilov and Pirallahi Islands in 2010

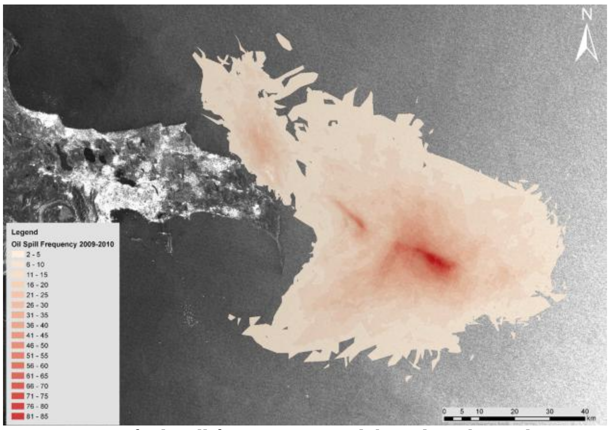

Fig. 8 Map of oil spill frequency around the Oil Rocks Settlement, Chilov and Pirallahi Islands in 2009–2010

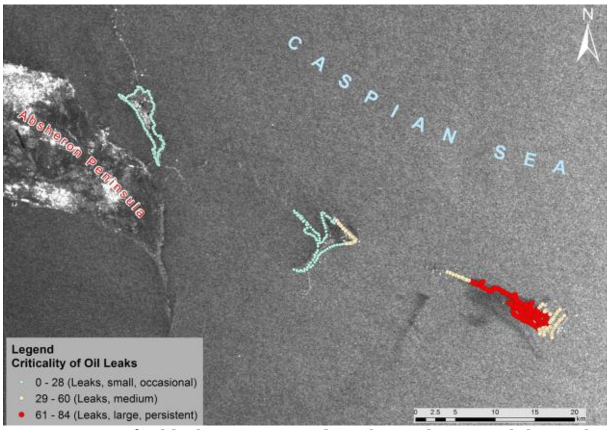

Fig. 9 Map of oil leak sources at Oil Rocks Settlement, Chilov and Pirallahi Islands based on the oil spill frequency 2009–2010

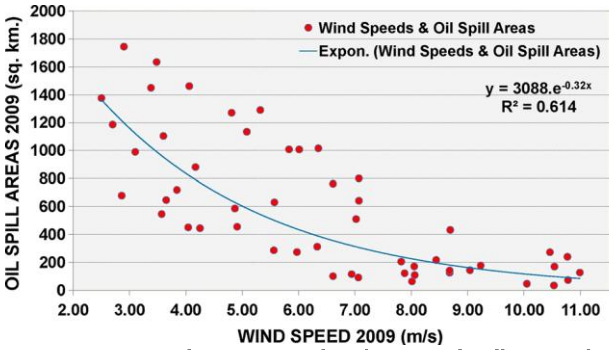

Fig. 10 Exponential regression analysis between oil spill areas and wind speeds in 2009

5. CONCLUSIONS

The count and area of oil spill frequency for the period of 2009–2010 significantly differed from individual spill frequencies in the years 2009 and 2010 showing the continuous spills of oil around the Oil Rocks Industrial Settlement, Chilov and Pirallahi Islands. This allowed to detect hot spots with high frequencies of oil spills, spatial distribution, and approximated oil leak sources for the planning of cleaning activities. The areas of detected oil spill frequencies are the following: 2–25 (4,658.83 sq. km.), 26–45 (302.83 sq. km.), and 46–75 (77.95 sq. km.). It was possible to observe that the most critical classes of oil leaks were located around the Oil Rocks Settlement. The computed frequency of large and persistent oil leaks was in the range of 61–84. The medium class of oil leak sources was observed around the Oil Rocks Settlements and Chilov Islands. Small and occasional leak sources were observed around Chilov and Pirallahi Islands. The exponential regression analysis between wind speeds and oil slick areas in 2009 with R^2 equal to 0.61 showed that larger oil spill areas were observed with lower wind speeds. The wind speed is one of the controlling factors of spatiotemporal changes of oil spill areas in the Caspian Sea. The Caspian Sea currents showed the dynamic movement patterns in different directions and speeds which explained multidirectional spatial distribution of oil spills, in particular around the Oil Rocks Settlement. The analysis also showed that the appearance of the oil slicks in the SAR imagery depends on the Caspian Sea conditions during the acquisition, in particular the wind speed. The best conditions are intermediate wind conditions (2.5–14 m/s) so that the oil can generally be detected by the SAR as dark areas in the imagery.

6. ACKNOWLEDGMENT

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