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Research on Oil Pollution of the Caspian Sea by GIS Systems

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Abstract

The Caspian Sea is the largest inland water body on Earth without a direct connection to the world's oceans, which makes it a unique water reservoir. This fact makes the Caspian Sea particularly vulnerable and subject to human influence, for example, pollution from shipping activities and oil transports by ships. Over the years, oil pollution has been the primary environmental problem of the Caspian Sea. In this paper, we present the results of our satellite survey in 2019 of the whole aquatic area of the Caspian Sea. These results reveal the spatial and temporal distribution of hydrocarbon films of various origins on the sea surface. Our primary attention focused on the main types of petroleum hydrocarbon films polluting the sea surface.

The research study shows results from a monitoring campaign in northern and central parts of the Caspian Sea (Kazakhstan sector) for the period from 2005 to 2012 (April–October), based on visual interpretation of radar images from ASAR ENVISAT. Radar data (529 radar images) such as ASAR_WSM_1P and ASAR_IM_1P were obtained from the archives of the European Space Agency. In 529 ASAR ENVISAT images, 160 images were selected, on which 329 oil spills were detected (Aliyev, 2003; Aliyev, 2010; Bayramov *et al.*, 2018; Airbus, 2012; Caspian, 2018).

We mapped the petroleum hydrocarbon pollution of the Caspian Sea surface on the base of satellite data. For each type of pollution, specific manifestation features were revealed, regions of regular pollution occurrence were outlined, and polluted areas were estimated. The relative contribution of every kind of pollution to the total oil pollution of the Caspian Sea is assessed on the base of satellite data. A comparison with the previous results of our long-term survey of the Caspian Sea is made (Aliyev, 2003; Bayramov *et al.,* 2018; Lavrova *et al.,* 2019; CIA, 2001).

Keywords: Caspian Sea, satellite monitoring, sea surface, oil pollution, ecological risks.

Introduction

Caspian region is the oil and gas production, shipping, fishing, the extraction of various salts and minerals (Caspian region is world famous for its oil and gas industry and production, shipping lanes, fishing industry and the extraction of various salts and minerals). The Caspian Sea pertains to the world largest oil-bearing regions. Total oil reserves of the Caspian Sea region are estimated at above 250 billion barrels (Aliyev, 2010). The explored oil resources in the Caspian Sea amount to about 10 billion tons. Oil and gas are being produced and transported on an ever-increasing scale that gives rise to many serious environmental and water management problems (Aliyev, 2010; Airbus, 2012; Caspian, 2018).

For many years, the primary environmental problem of the Caspian Sea has been oil pollution, which is associated both with oil production and transportation, as well as changes in sea level, leading to secondary pollution, river runoff and even seismic activity, provoking natural oil seeps from the bottom of the sea. Oil pollution inhibits the development of phytobenthos and phytoplankton, reduces oxygen production, and accumulates in the bottom sediments. An increase of an oil film on the water surface up to 0.1 mm interferes the process of gas exchange and threatens the death of hydrobionts. This phenomenon is already observed on reaching 1 g/m2 of oil on the water surface. Oil produces a hazardous effect on marine organisms – from bacteria and phytoplankton to fish. A concentration of oil products of 0.01 mg/L becomes dangerous to fish, 0.1 mg/L for phytoplankton, 100 mg/L for macroalgae (Caspian, 2018; Lavrova *et al.,* 2019; CIA, 2001; ESA, 2015).

Present-day monitoring of oil pollution at sea is done through widely used satellite radar images. Known as ASAR (advanced synthetic aperture radar), it is well established due to a number of advantages it has over other sources. Radar images do not depend on weather conditions, cloud cover, or light conditions and, at the same time, have a sufficiently good spatial resolution and cover large areas (Fiscella *et al.,* 2000; Ivanov and Zatyagalova 2008; Kamagate 2011). Crude oil and oil products that enter the sea, depending on their physical and chemical parameters, form surface films on the water of various thicknesses (from a few centimeters to only fractions of millimeters) (Lavrova *et al.,* 2019).

This distinguishes them from films, such as biological surfactants (produced by plankton and fish), that are able to spread monomolecular layers. This means that more viscous and difficult oily mixture can be observed on radar images at higher wind speeds as well, while the surfactant films will disappear (Ivanov *et al.,* 2004a,b; Brekke and Solberg, 2005). Due to its high sensitivity to the surface roughness of the sea, the radar images are very good at fixating on floating oil. Under wind conditions from 2.5–3 m/s to 10–12 m/s, oil dampens ripple waves and forms a smooth layer on the surface, which, in turn, appears on radar images as dark patches on the brighter water surface (ESA, 1998b; Ivanov and Zatyagalova, 2008).

The main objective of this research study is to assess the level of oil pollution based on radar satellite images ASAR (ENVISAT), for the period 2005–2012, in the Kazakhstan sector of the Caspian Sea. The tasks included are as follows: detection of oil slicks, identification of possible sources of contamination, identification of areas of the greatest congestion of oil slicks, and digitalization of oil spills and creation of an overall pollution map. Further, a robust framework to monitor oil spills using radar data and additional GIS data is developed and explained in the data/method section (Lavrova *et al.*, 2019; CIA, 2001; ESA, 2000b; Fiscella *et al.*, 2000; Zonn, 2006).

In 2019 the sea surface oil pollution survey was based on the combined use of satellite imagery obtained by sensors installed on various satellites and operating in different bands of electromagnetic waves. Data in visible and microwave ranges provided the primary material for the analysis. We used high-resolution radar imagery data obtained by SARs onboard Sentinel-1A and -1B satellites. The oil spills on the sea surface have diverse characteristics and scales, and it is not always possible to pinpoint typical features that would allow us to detect them in satellite images with 100% confidence. For more robust interpretation, the SAR data is complemented by other satellite data on the sea surface and water condition, sea surface temperature, and mesoscale water dynamics. We used data taken in visible bands by MSI sensors onboard of Sentinel-2A, -2B satellites and by OLI-TIRS sensor of Landsat-8 satellite (Fiscella *et al.*, 2000; Zonn, 2006).

The optical satellite sensors depend on reflected sunlight and are among the “passive” remote sensing systems. The radar systems with their own radiation source belong to the “active” systems, as reflected signals are recorded to the sensor. The radar sensors are due to their active lighting and the ability of microwaves to penetrate clouds, haze, fog, and smoke, regardless of the light conditions and the weather (Albertz, 2001; Soergel, 2006). In addition, the microwave range of the electromagnetic spectrum with a wavelength of 7 mm is affected by weather conditions (Lusch, 1999) (Fig.1). (EES, 2018) The process of radar recording depends on several individual parameters.

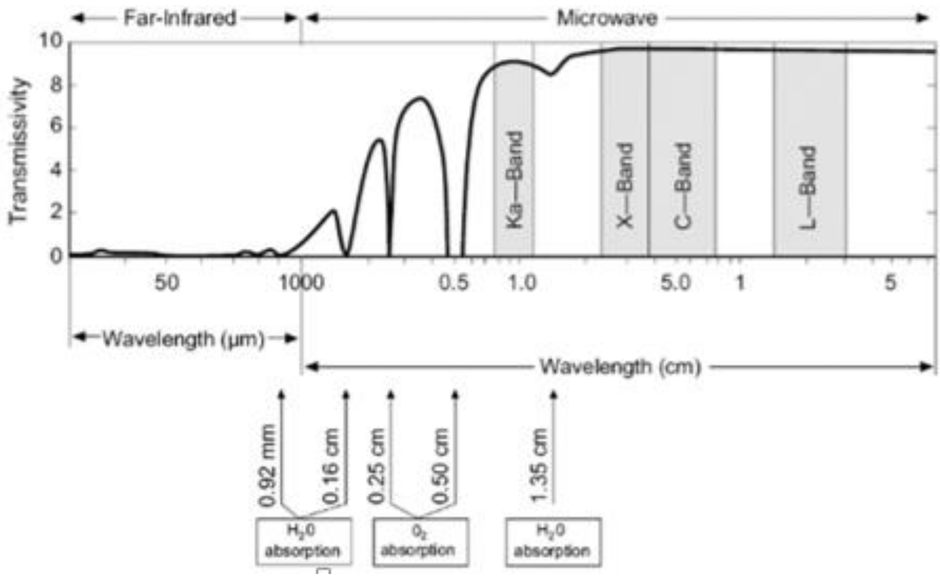


Figure 1. Microwave atmospheric permeability
(Reproduced with the permission from Lusch, 1999).

When there is wind conditions of up to 2.5 m/s, a calm zone is formed, and the oil slick is drained from the water surface. Conversely, if wind speeds greater than 12 m/s, oil slicks mix with water. In both cases, identification is not possible (Fig. 2). The most optimal conditions are wind speeds of 3–8 m/s, when the oil is clearly seen/observed/traced on the radar image as dark patches on a bright background water surface (Ivanov and Zatyagalova, 2007; Kamagate, 2011) (Zonn, 2006; Mityagina and Lavrova, 2015; Holstein *et al.*, 2016; Marina, 2019).

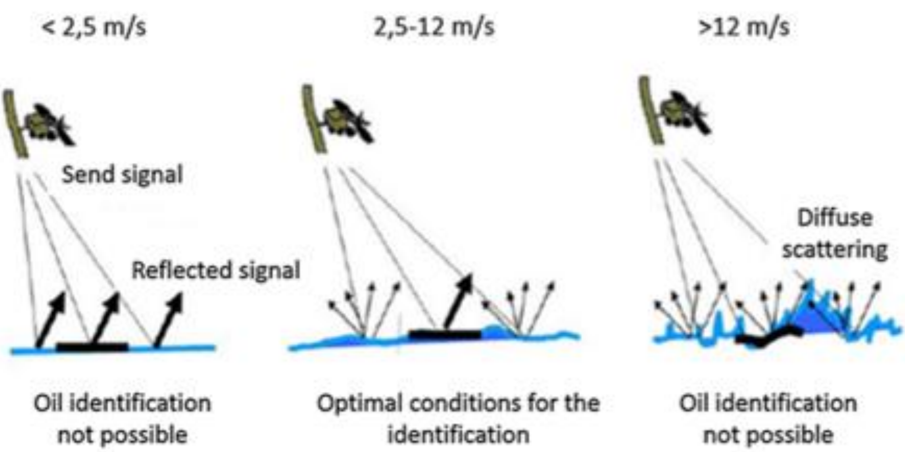


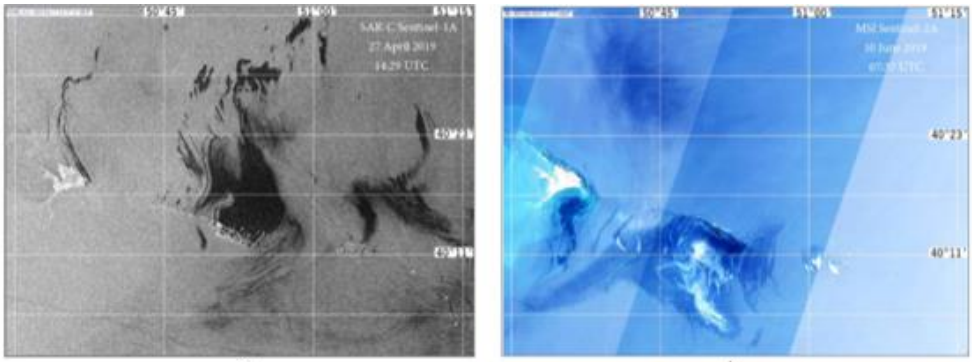
Figure 2. Wind conditions for oil spill detection with the radar sensors

The area under consideration is characterized by wind speed of 5–8 m/s, which are the most favorable conditions for the detection of oil slicks. Another limitation is the existence of look-alike effects and processes on the water surface and in the lower atmosphere, which also cause dark patches in radar images (Espedal, 1998). These may be low wind areas, shear zones, grease ice, upwelling, rain cells, biological films (surfactants), algae blooms or the internal and atmospheric gravity waves etc. The main problem in the identification of oil pollution is to discriminate these natural effects from the oil pollution (Brekke and Solberg 2005). For this purpose, the oil slick properties (shape, size, location relative to infrastructure, contrast, texture, form of the boundaries of slicks) can be used as well, as meteorological and oceanographic information or satellite data in the visible and infrared ranges (Ivanov and Zatyagalova, 2008; EES, 2018; Mityagina, and Lavrova, 2015; Marin *et al.,* 2016; Marina *et al.,* 2019).

Oil pollution in the “Oil Rock” oil-producing area. The most important source of the open sea surface pollutions in the central zone of the Caspian Sea and in the area of Absheron and Baku archipelagoes is the ingress of the oil caused by the oil production and by oil outflow from natural and artificial seepages at the sea bottom. From the late 19th century, Azerbaijan pioneered the development of shelf and offshore oilfields, and it was the first country to suffer from sea surface pollution.

In the VIS image obtained in the sun-glint area, oil-containing films have increased brightness and appear as light structures surrounded by a dark halo; the polluted area is of about 420 km^2 in this case (Fig. 3b). Sun-glint refers to the reflection of solar radiation from the sea surface observed by optical sensors when sunlight’s incidence angle is equal to the angle of reflection. In the sun-glint region, areas covered by films appear brighter because the surface film reduces the sea surface roughness and a higher number of local elements are present, reflecting light to the sensor. It should be added that the oil film on the VIS images may be visible even better than in the radar images, since the observed contrasts are caused not only by smoothing surface waves by the oil slick, but also by the differences in the optical characteristics of clean water and the oil film (Martin *et al.,* 2016; Marina *et al.,* 2019).

However, usage of optical data is heavily constrained by illumination and cloud-free requirements, so they have been lost by far to radar data in application to continual monitoring and gathering statistics. Nevertheless, optical data, especially images with sun-glint effect, often help to interpret radar data and decide on the origin of a slick film; whether it is an oil or biogenic film, because oil and biogenic films are manifested differently in optical data. Oil films are brighter and have shiny signatures in color composites. Oil-producing platforms connected by piers are visible in both images. (EES, 2018; Marina *et al.,* 2019).



a b

Figure 3. Examples of manifestations of the sea surface oil pollution in the oil-producing area “Oil Rocks” in satellite images:
a) a part of a VV-polarized Sentinel-1A image acquired on 27 April 2019; b) a part of a color MSI Sentinel-2A image (composite of 4, 3 and 2 spectral channels) acquired on 10 June 2019.

We should admit that the sea surface pollution near these drilling platforms is caused not only by “dirty” oil production techniques (the oil production and oil well drilling, the underwater oil rig repair, oil outflow during pipeline breaks), even before drilling started at “Oil Rocks” in 1949. The sea surface in this area was famous for its natural oil slicks. The amount of the oil ingress from the seabed to the sea in this area can vary between 100 and 500 tons per day. The spread and evolution of the oil patch, which is always present near the oil drilling site, depends on the meteorological conditions. The oil-producing area “Oil Rocks” can be used as a natural laboratory for studying the effect of wind conditions on oil patches as well as on formation of oil slick signatures in radar images (Mityagina and Lavrova, 2015; Mityagina and Lavrova, 2016). Methods of the monitoring the sea surface oil pollution, developed here by means of remote sensing, will be applied to other regions.

All images received from the ESA archive (529) were visually examined for the presence of dark patches on a bright background of the water surface using programs EnviView (Application to open ENVISAT data file) and NEST (Next ESA SAR Toolbox). As a result, all images with the specific dimming have been selected. Afterward, selected images were geo-corrected and converted from the format N1 (ENVISAT) in GeoTIFF or ENVI format using NEST for follow-up processing in ArcGIS. These images were analyzed in ArcGIS by integrating additional information (boundaries, bathymetry, coastline, infrastructure, etc.). The filtering was performed if better imaging was necessary. At this stage, the images were selected which contained dark patches and were within the boundaries of the

Kazakhstan sector of the Caspian Sea, and that held a high probability of being caused by oil pollution.

Many ship slicks have a very distinctive line appearance. Pictures taken during the discharge of oil or immediately after the reset can be reviewed and the probable polluter can be quickly identified (The picture shows the ship as a bright point of light located in the immediate vicinity of the spill.). Thus, Fig. 9 reflects oil dumping with moving ships, repeated in the southwest direction (discontinuous band stretching for many kilometers with a bright point at the beginning of conformity of the ship). If necessary, the use of an automated system of tracking ships AIS (automatic identification system) can determine the type and identity of the ship, and, furthermore, can bring the perpetrators to justice.

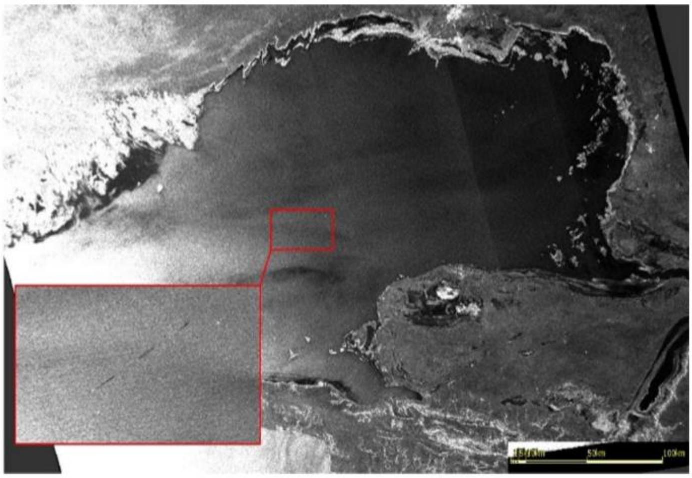


Figure. 4. Northern Caspian Sea.

After identification, the slicks were digitized in a vector layer placed on their cartographical basis. Figure 3a shows the shipping situation in the region for the year. Figure 3b shows a map of the distribution of oil slicks. Joint analysis of maps to navigation and oil pollution shows that the majority of slicks are concentrated mainly along the shipping routes southbound from the port of Aktau, pointed in the directions of Baku (Azerbaijan), Neka (Iran), and Turkmenbashi (Turkmenistan), which may indicate a greater intensity of navigation in this direction, as well as in the proximity of the port of Aktau, where the anchorage is located. Slicks form near the port of Aktau (slicks are rounded) indicate discharges of ship at anchor. Some numbers of slicks were detected in the northern part of the port Aktau in the Caspian Sea, in the direction of Astrakhan (Russia), Atyrau (Kazakhstan), and the Kashagan oil field. In the northeastern part, the intensity of shipping is related mainly to fishing and activity on Kashagan oil field.

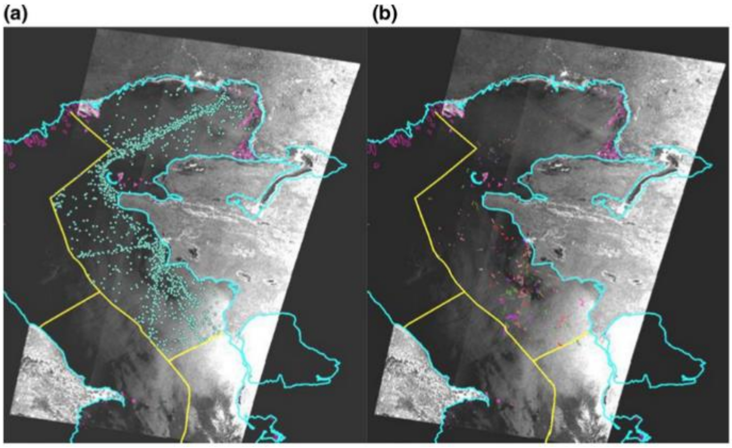


Figure. 5. The annual ship traffic in the waters of the Kazakhstan sector of the Caspian Sea

The discharge from the vessel produced during filming. The photograph shows the ship (bright spot)- presumably the originator of oil dumping. The nature and form of spills indicate repeated reset during movement of the ship in a SW direction. The total surface of the spills is 1.87 km^2. Fragment of WSM ENVISAT radar images from September 13, 2009 (EES, 2018).

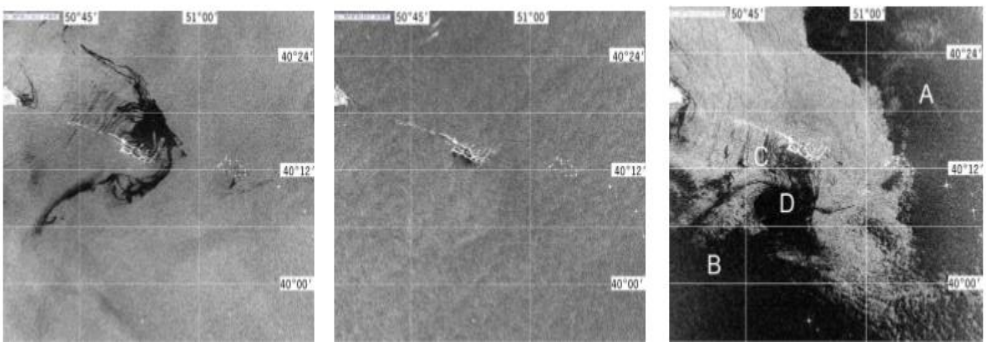


Figure 6. a) A part of a VV-polarized Sentinel-1 SAR image of 27 March 2019, 14:37 UTC, showing oil patches near the oil platform. Total area of the oil slick is 375 km2; b) a part of a VV-polarized Sentinel-1 SAR image of 01 July 2019, 14:37 UTC, showing the sea surface near the oil platform; c) a part of a VV-polarized Sentinel-1 SAR image of 14 January 2019, 14:37 UTC, obtained at low wind. (Ecologica Montenegrina, 25, 2019, 91-105)

Fig. 6a (left). The annual ship traffic in the waters of the Kazakhstan sector of the Caspian Sea according to the satellite ENVISAT. The blue color shows the court. b (right) A map of all oil spills detected by ASAR ENVISAT (ESA) in the Kazakhstan sector of the Caspian Sea for the period 2005–2012 (April–October) (EES, 2018).

Radar images were taken but under less favorable wind speeds, higher than 10 m/s as well as in the presence of active processes in the atmosphere-ocean boundary layer reveal very small (or not at all) dark areas of decreased radar backscatter near the oil rig. This situation occurs because at high wind speeds (exceeding 9-10 m/s) both oil and biogenic polluting films are disrupted by wind and waves, and cannot always be identified in radar images (Mityagina and Lavrova, 2016). A combination of strong wind and waves inhibits the formation of an oil slick. Moreover, considerable variations of NRCS caused by atmospheric signatures can sometimes cover the significant part of a radar image. It sometimes makes it impossible to identify oil patches on the sea surface under such conditions.

All the factors mentioned above lead to the high probability of the underestimation of the polluted area size under high winds and disturbed atmospheres. A Sentinel-1 SAR image taken over the oil-producing area “Oil Rocks” is depicted in Fig. 6b. Wind field variations caused by convective processes in the near-surface atmosphere produce prominent cellular structure in the radar image, and oil slick cannot be easily identified in this image.

On the other hand, a large number of low backscatter areas is seen in radar images obtained under low near-surface wind that are not related to the presence of oil-containing films on the sea surface. The capillary-gravity component of the sea surface wave field may not develop under weak-to-no-wind conditions. Low wind areas seen in radar images in the vicinity of oil drilling platforms can be misinterpreted as oil slicks. The existence of these low scattering (dark) areas in radar images increases the “false alarm” probability in oil pollution monitoring. Hence, sizes of polluted areas derived from radar data, taken at low winds, can be overestimated. Fig. 6c illustrates this situation. Vast dark areas of decreased NRCS are seen in the Sentinal-1A SAR-C image taken over the central part of the Caspian Sea. Areas marked by “A” and “B” represent low-wind areas. Elongated areas covered by oil film are present on the sea surface near the oil-producing platform resulting in significant attenuation of short gravity-capillary waves and formation of slicks (marked by “C”). The interpretation of the area “D” where the sea surface is smooth can lead, generally speaking, to ambiguous results.

For the study, we examined all Sentinal-1A and 1-B images of the Caspian Sea over the «Oil Rocks» area for the year 2019 obtained to the data of writing this paper

(August 2019). It was found that 65% of radar images taken over the oil-producing area “Oil Rocks” bore signatures of oil patches near the oil platforms. No slicks were found in the remaining images because high/low winds prevented them from being detected. These results were compared with those based on ASAR Envisat imagery for the period from January 2010 to December 2011 and on Sentinel-1 SAR imagery taken from October 2014 to June 2015 (Mityagina, Lavrova, 2015). It was found that 69.3% of radar images of the test area contained signatures of oil patches near the oil rigs. No slick structures were seen in the remaining images because high/low winds prevented them from being detected by SAR. The corresponding statistics are shown in Fig. 7.

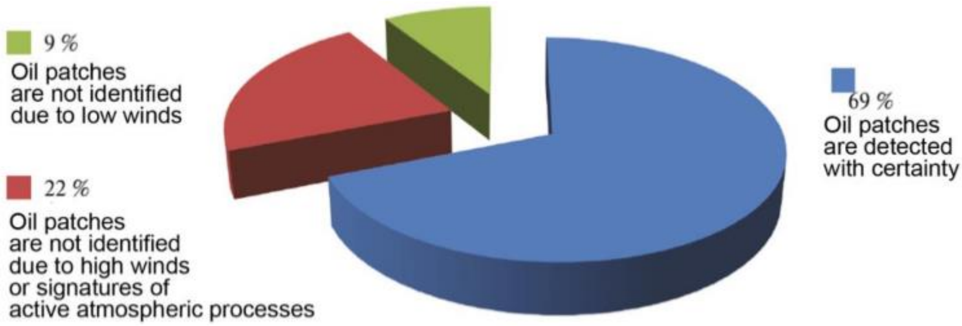


Figure 7. Statistics on the frequency of detection of oil patches in the “Oil Rocks” oil producing area in SAR images in dependence on near-surface winds. (Ecologica Montenegrina, 25, 2019, 91-105)

Oil pollution in offshore oil-producing areas. Azerbaijan became the first country which began to exploit the offshore deposits of oil and gas. Now, Russia, Kazakhstan, and Turkmenistan are also developing offshore oil fields in the north-western, north-eastern and eastern parts of the Caspian Sea correspondingly. Only Iran has not yet exploited oil deposits in the Caspian Sea. This year, only several single oil slicks of the small area were detected in the Cheleken oil production area, owned by Turkmenistan. These slicks were located near the shipping routes and occurred most likely during the oil overload. No films of crude oil were detected in satellite data taken over the northern part of the Caspian Sea, where a current production of oil takes place. Nevertheless, the growing rate of oil production and transportation, as well as the development of new oil fields, especially on the shelf, lead to an increase in the probability of oil pollution, despite the fact that new technologies (such as zero recovery, plans for the prevention and elimination of emergency oil and oil products etc.) and all the measures are taken.

One should be conscious on the fact that the specific and particular features of the Caspian Sea, especially in its shallow northern part, indicate that one serious oil spill is enough to inflict a fatal blow on sturgeon flocks and bird nests. In general, oil pollution can be associated with any operations for the extraction and transportation of oil and its scale can be either minor or catastrophic. Unfortunately, accidents regularly occur on the oil-producing sites in the Caspian Sea, the details of which are not always known to the public (Zhiltsov *et al.*, 2016). In this regard, it is necessary to note the role of satellite remote sensing, which allows for continuous monitoring of areas of accidents and for revealing aftereffects. For example, an intense fire occurred on December 4, 2015, on the offshore stationary platform in the Azerbaijani part of the Caspian Sea at the Guneshli field. The fire was caused by a rupture of a high-pressure gas pipeline due to storm conditions which lead to depressurization of the oil well.

In the satellite true-color image (Fig. 8a) taken over the area of interest on December 8, 2015, the plume of smoke from the burning platform is seen. The smoke can be traced to the center of the Southern Caspian throughout almost 170 km. The burning lasted 13 days till December 17, 2015. Oil pollution in the adjacent water area was observed in SAR images as an aftereffect of the fire (Fig. 8b).

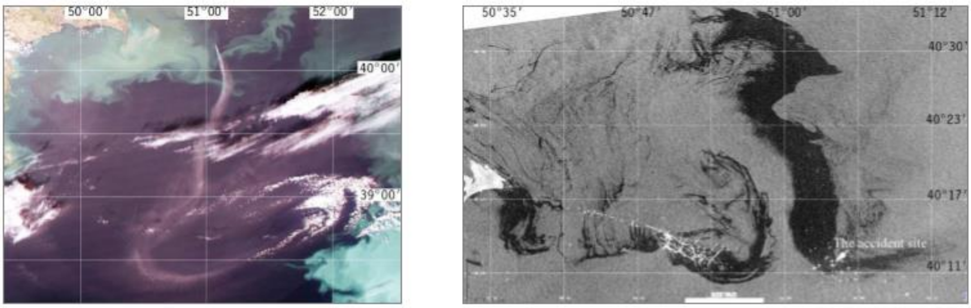


Figure 8. Manifestations of the fire aftereffects in satellite images: a) the smoke plume from a burning platform. A part of a color composite (R: 620-670 nm, G: 545-55 nm, B: 459-479 nm) MODIS Aqua image of 8 December 2015, 09:00 UTC; b) sea surface oil pollution caused by the accident at the platform. A part of SAR Sentinal-1A image of 13 December 2015, 14:37 UTC. The area of oil pollution due to the accident is 263 km2. (Ecologica Montenegrina, 25, 2019, 91-105)

Results

The result of the analysis revealed 529 radar images of the sea surface (ASAR WSM, ASAR IM) in the study area for the period 2005–2012 (April–October). Only research satellite surveys from April to October were chosen, as throughout the remaining period, most of the study area was ice covered which made the identification of oil pollutions impossible. Uneven numbers of images obtained in different years for the study area made it impossible to analyze the pattern of an increase or decrease in the number of slicks for different periods of time. Therefore, the total assessment of oil pollution was undertaken in the study area.

The results of our satellite monitoring have made it possible to retrieve the persistent pattern of the Caspian Sea surface oil pollution. This pattern is determined by the ways through which petroleum enters the aquatic area of the Caspian Sea. The main elements of this pattern are depicted in Fig.11. Regions of regular occurrence of specific types of oil pollution are outlined where continuous satellite monitoring should be implemented. The Absheron Sill and the Baku Archipelago - natural leakages of liquid hydrocarbons fed by underground deposits occurs here. According to modern concepts, the contemporary process of oil and gas formation occurs in the Absheron Sill area.

1. The western part of the Southern Caspian - a large number of mud volcanoes is located on the seabed here. According to published data (Zonn *et al.*, 2010), millions of tons of oil and billions of cubic meters of gas are emitted annually through the mouths of mud volcanoes into the waters of the Caspian Sea. Natural hydrocarbons are partially dispersed in seawater, partially evaporated into the atmosphere.

2. Natural hydrocarbon seafloor seeps off the south-western coast in the Gilan Province of Iran eastward of the Sefid Rud Cape.

3. Natural hydrocarbon seafloor seeps westward of Cheleken Peninsula which belongs administratively to Turkmenistan.

4. The south-eastern shelf - There is a risk of oil pollution in case of accidents on offshore oil-producing platforms of Turkmenistan and underwater oil pipelines.

5. The north-eastern shelf - There is a risk of oil pollution in case of accidents on offshore oil-producing platforms of Kazakhstan and underwater oil pipelines.

6. The north-western shelf - There is a risk of oil pollution in case of accidents on offshore oil-producing platforms of Russia and underwater oil pipelines.

7. Ship discharges along main shipping routes.

The bulk of international oil shipments is carried out by oil tankers. Each of the Caspian countries makes efforts to create and develop its tanker fleet and port infrastructure. Most of the oil is transported through the seaport of Aktau (Kazakhstan) to the Port of Baku (Azerbaijan) and the Port of Makhachkala (Russia). It is planned to expand tanker shipments of oil from the eastern coast of the Caspian

Sea (Kashagan oil field) to the west to the Baku-Tbilisi-Ceyhan oil pipeline within the framework of the projected Kazakhstan Caspian Transportation System (Zhiltsov *et al.,* 2016).

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