Modelling of possible tanker accident oil spills in the Istanbul Strait in order to demonstrate the dispersion and toxic effects of oil pollution

Serdar YILDIZ[a], V. Zülal SÖNMEZ[b], Özkan UĞURLU[c], Nüket SİVRİ[d], Sean LOUGHNEY[e] and Jin WANG[f]

[a]Maritime Transportation and Management Engineering Department, Karadeniz Technical University, Trabzon, Turkey, serdaryildiz@ktu.edu.tr

[b]Department of Environmental Engineering, İstanbul University-Cerrahpaşa, İstanbul, Turkey, zulal.sonmez@iuc.edu.tr

[c]Maritime Transportation and Management Engineering Department, Ordu University, Ordu, Turkey, ougurlu@odu.edu.tr; ozkanugurlu24@hotmail.com 00905058179839 (corresponding author)

[d]Department of Environmental Engineering, İstanbul University-Cerrahpaşa, İstanbul, Turkey, nuket@iuc.edu.tr

[e]Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Faculty of Engineering and Technology, Liverpool John Moores University, Liverpool, UK, S.Loughney@ljmu.ac.uk

[f]Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Faculty of Engineering and Technology, Liverpool John Moores University, Liverpool, UK, J.Wang@ljmu.ac.uk

ABSTRACT

Countries located on the Black Sea coast perform most of their sea trade through the Istanbul Strait (IS). Approximately 50,000 ships pass through the IS each year, with crude oil tankers making up the majority. Thus, the aim of the study is to determine the acute toxic effect of oil pollution that may occur as a result of crude oil tanker accidents in the IS. By utilising data related to accidents that have occurred in the IS, locations of concentrated tanker accidents, or "hot spots", were determined by Kernel Density Analysis. Subsequently, the distribution of potential leaks following an oil tanker accident, within these hot spots, is modelled with GNOME software. Finally, acute toxicity caused by oil pollution in the marine ecosystem is determined by *Aliivibrio fischeri* luminescent bacteria toxicity test. In this research, 5 hot spots are identified, where the maximum calculated amount of oil that can reach the coastline after 72 hours is 3,096 metric tons. Similarly, oil pollution can affect a total coastline of 30-35 km. Furthermore, it was determined that after the oil was diluted in seawater, at a ratio of 1:200,000, the toxic effects decrease (EC_{50} above 100 mg/L), yet the chronic effects may still continue.
The results of this study may serve as a reference for coastal state authorities to develop emergency response plans. Having this valuable knowledge of where high risk accidents are most concentrated, where the accidents occur intensely, which areas can be affected by the pollution, the duration of the pollution effects, and the distance between the areas, will help

determine the number of intervention stations to be installed, their locations, and equipment to be installed to the stations.

Key Words: Oil pollution, Acute toxicity, Istanbul Strait, Marine accidents, Geographic Information System

1. Introduction

Straits and narrow waterways throughout the globe are often heavily congested, and consequently have an increased number of vessel accidents (Ince and Topuz 2004; Bubbico et al. 2009; Uğurlu et al. 2016). The Istanbul Strait (IS), the junction point of the east and the west, is one of the most important narrow passages in the world and is the only access point for vessels entering or leaving the Black Sea. Therefore, countries with a coastline on the Black Sea maintain their natural maritime trade through the IS (Aydogdu et al. 2012; Kosyan and Velikova 2016).

It is known that 20% of the entire cargo transported by sea is crude oil (UNCTAD 2019), and a significant percentage of exported petroleum products reach the world through the Turkish Straits (Akten 2004; DTGM 2019). This is remarkable in terms of environmental pollution pressure and potential security threats, as well as military, political and commercial concerns (Doğan and Burak 2007; Güneş 2007; Koldemir 2011; Kaptan et al. 2020).

The worst scenario in shipping is, of course, fatal accidents. However, catastrophic ecological accidents, which cannot be compensated for financially and where ecosystem damage remains for many years, can have parable consequences to fatal accidents (Arslan 2018). The most important step after such ecological accidents is the rapid implementation of preventive measures by -maritime authorities. Thus, it is possible to overcome acute (short term) and chronic (long term) effects of the pollution with less damage and partial losses. Acute and chronic effects are physiological reactions in humans or animals resulting in serious symptoms that develop rapidly during short-term (acute) or long-term (chronic) exposure to toxic chemicals or substances (Safeopedia 2020). One of the most important examples for the IS is the collision involving the Motor Tanker (M/T) Independenta (1979). Subsequent late interventions -following the Independenta spill caused considerable economic and ecological damage to the fishing industry (Doğan and Burak 2007; Chauvin et al. 2013; Uğurlu et al. 2015a; Öztürk and Balcıoğlu 2017). Furthermore, following the Volganeft 248 accident in the Black Sea-Kerch Strait in 1999, the chronic effect of the damage caused by oil pollution on sea creatures remains today (Uğurlu et al. 2020).

Recent studies suggest that during an oil spill, the toxicity testing of seawater may be the only safe tool to assess the impact of the spill on coastal organisms. Oil spill contingency plans focus on the follow-up and prediction of the trajectory of the surficial oil slick. This causes heavy mortality rates in birds and mammals, but a period of long exposure is the most dangerous for small size plankton and nekton organisms in aquatic ecosystems (Beiras and Alvarez, 2006, Chang et al. 2014). Several studies have found that the acute exposure of various phytoplanktonic species (*Phaeodactylum tricornutum, Skeletonema costatum, Thalassiosira pseudonana, Cyclotella caspia, Chlorella vulgaris, Zooxanthella croadriz tica, Nitzschia closterium f. minutissima, Platymonas subcordiformis, Heterocapsa triquetra; Ditylum brightwellii*) to different oil Water Accommodated Fractions (WAF) varies between 1.01 µg/L - 114.00 mg/L (Yu et al. 2002; Liu et al. 2006; Bopp and Lettieri, 2007; Wei et al. 2007; Wang et al. 2008; Jiang et al. 2010; Ozhan and Bargu, 2014a; Ozhan and Bargu, 2014b; Ozhan et al. 2014).

In addition to the sensitive planktonic forms and several other marine species, such as Seaweed (*Codium tomentosum, Codium barbata*), Algae (*Ulva lactuca*), Molluscs, (*Mytilus galloprovincialis, Ostrea edulis, Patella vulgata*), Crustacea (*Crangon crangon*), and Fish (*Gobius niger, Solea, Trigla lucerna*) have been under threat because of the oil spill (Öztürk et al. 2006; Taş et al. 2011; Bozkurtoğlu 2017; Öz and Demirel 2018). Following such pollution accidents, long-term damage clearly occurs in marine ecosystems, with human health also negatively affected. The long-term damage that can be observed at all levels, from microscopic organisms to macro-organisms, reveals the importance of required emergency measures against these types of accidents.

Crude oil and its constituent chemicals are common environmental toxicants in aquatic environments worldwide and have been the subject of intense research for decades. Importantly, aquatic environments are also the sites of numerous other environmental disturbances that can impact the endemic fauna. While there have been a number of attempts to explore the potential additive and synergistic effects of oil exposure and environmental stressors, many of these efforts have focused on the cumulative effects on typical toxicological endpoints (e.g., survival, growth, reproduction, and cellular damage). Few studies have investigated the impact that oil exposure may have on the ability of exposed animals to tolerate typically encountered environmental stressors, despite the fact that this is an important consideration when identifying oil spills in an ecological context (Khursigara et al. 2019).

Oil spills from marine accidents contribute to 20% of all oil pollution in the oil transportation industry (Halsey and Abel 2002; de la Huz et al. 2005). The acute effect of a possible tanker accident on marine ecosystems can be devastating in the IS (Topakoğlu 2004). Therefore, the study aims to determine high density oil tanker accident areas and the subsequent toxic effects of the potential oil pollution.

The study is conducted in three main steps. Firstly, high-density areas where tanker accidents are most likely to occur are determined. To satisfy this step, tanker accidents that occurred in IS were examined through the Kernel density analysis method by locating accidents on an electronic map of the IS. Thus this led to the development of the "IS tanker accident risk map (Kernel density map)". Secondly, the sea and coastal locations that may be affected by oil pollution are determined. To fulfil this step, crude oil spill simulation modelling was conducted, with the pollution origin points located where tanker accidents frequently occur. The General National Oceanic and Atmospheric Administration’s (NOAA) Oil Modeling Environment (GNOME) software was used to simulate the oil spills. Thus, the areas that the oil spill can reach and how it spreads over a 72-hour uninterrupted period, under the effect of sea and atmospheric conditions, are determined. Thirdly and finally, the potential acute toxic effects of oil pollution in the identified areas and the potential effects on the marine ecosystem are determined. A wide range of bioassays using fish and other aquatic organisms from several trophic levels have been used for biological monitoring and toxicity assessments. Unfortunately, most of these bioassays are relatively long (24, 48, 72, 96 and 120 hours), comparatively expensive, require sophisticated facilities, and require a great deal of professional competence for data interpretation. Consequently, for quick screening of effluents and chemicals for toxicity and to determine if additional sophisticated tests are required, simple, rapid, sensitive, and inexpensive assays could be more useful. Microorganisms, in particular bacteria, have several attributes which make them attractive for use in such tests for toxicity testing (Coleman and Qureshi 1985). *Aliivibrio fischeri* luminescent bacteria toxicity test was carried out at short intervals of 5, 15 and 30 minutes. As a result, the extent of damage from toxicity in the ecosystem is clarified and suggestions for mitigation measures are presented. This paper provides an alternative assessment method for the maximum range of pollution from an oil spill and the subsequent toxicity, in narrow waterways that contain various ecosystems and organisms.

2. Material and Method

In this study, simulations were outlined to demonstrate the potential effects of oil tanker accidents in the IS. By creating and analysing the simulation scenarios, high-density areas were identified, and oil spills were simulated in these areas. Subsequently, the potential levels of acute toxicity in the ecosystem from oil pollution are determined. The steps of the study are outlined in the following sections.

2.1. Determination of Accident-Prone Areas

At this stage, oil tanker accidents that have occurred in the IS between 2003 and 2018 are investigated, and accident categories that can lead to oil pollution are limited to collision/contact, grounding and sinking. Other types of accidents that are not directly related to pollution (machinery failure, man overboard, occupational accident, etc.) were excluded from the study. Collision accidents are defined as two or more moving ships striking with each other. Contact is defined as a ship striking a stationary ship or shore structure/static structure. Grounding is defined as ships striking the seabed, shore, or underwater wrecks. Sinking accidents are flooding of ships with water and loss of floating ability for various reasons (IMO 2008). These marine accidents were obtained from the databases of the Marine Accidents Investigation Commission (DEKIK) and the Accident Investigation Review Board (KAIK) of the Turkish Ministry of Transport and Infrastructure (KAIK 2018). The data set of the study includes a total of 33 accident positions from 33 accident reports. The geographical scope is limited to the sea area from the northern entrance of the IS (the whole of the Turkeli sector) to the south exit (the Marmara sector). At this point, a spatial analysis of the accidents in the outlined area is conducted. The Kernel Density Estimation (KDE) method was applied using ArcMap 10.5 software for spatial analysis (ESRI 2017). In this study, a marine accident risk map was created using the Kernel Density Analysis method. In the Kernel Density Analysis Method, high-density areas are determined by reference to the positions where the accidents have previously occurred and the distances between the positions of the accidents (Silverman 1986; Wu and Mielniczuk 2002). The main purpose of Kernel Density Analysis is to create density distribution (risk) maps in the desired search radius and bandwidth from the main positions where the accidents occur (Bonnier et al. 2019). As a result, a "Marine Accidents Risk Map" was developed for tanker ships in the IS, and high-density areas for tankers are identified.

2.2. Oil Spill Modelling

In this step, the distribution of an oil spill from a tanker accident in the previously identified high-density areas are simulated. GNOME is a simulation software developed by NOAA's Hazardous Materials Response Division (HazMat) for aiding hazardous spill response such as oil, diesel, kerosene, and fuel oil, and is publicly available (Başar 2010; Beegle-Krause et al. 2003; GNOME 2017; Dong et al. 2019). GNOME supports many different modelling types (timed triangle, rectangular or curved grids) and many different file formats (ASCII, netCDF or BNA) so that simulation can be used worldwide (Beegle-Krause et al. 2003; Basar et al. 2018).

The IS has variable subsea and surface currents, and it can be seen that the surface currents generally flow north to south, with current speeds reaching 4 knots. A global custom map generator was used to obtain the geographical data for the area while Hybrid Coordinate Ocean Model (HYCOM) databases and a NOAA global shoreline database were used to obtain the oceanographic data and coastline data, respectively (GOODS 2020; SWAN 2020). The information within these databases is managed by NOAA and the data is provided by several national and international institutions. The geographical and oceanographic maps, required for this research, were obtained from these databases as separate layers (shoreline base map layer, surface and deep current layer and wind layer) for the region with a latitude of 40°-42° North and a longitude of 28°-30° East. The maps were then combined using the GNOME Diagnostic tool. In simulation modelling, seasonal currents and the dominant wind direction were considered. The direction and intensity of the prevailing wind were obtained using the Simulating WAves Nearshore (SWAN) module of the General Directorate of Meteorology and NOAA's NCEP Global Forecast System (GFS) (GOODS 2020; SWAN 2020). In the tanker accident simulations, it is assumed that only one of the cargo tanks is damaged and ruptured.

When the statistics of the ships passing through the IS are examined, it can be seen that in 2019, of the 41,112 ships that passed through the IS; 8,396 are tanker vessels (20%). Approximately 70% of tanker ships that pass through the IS have a length of 100-200m (DTGM 2019). Based on this information, it can be said that tanker type vessels passing through the IS are mostly Handysize (15,000-35,000 DWT). The maximum amount of oil that a crude oil ship of this size can load in one tank is approximately 5,000 metric tons (MT). Therefore, the spill of 5,000 MT crude oil from a single tank has been simulated, that is an assumption made for these scenarios. This assumption has been made to ensure that the amount of oil spilled is constant and consistent across all scenarios. The study aims to demonstrate how the size of the disaster can change with the same amount of spillage (5,000MT), on the same date, in the same weather and sea conditions, by changing the accident position.

Thus, in this phase of the study both the distribution map of oil pollution and the coastal areas that could be affected by the pollution are determined, and emergency response areas are revealed in the event of an accident.

2.2.1. Geographic Information Systems (GIS) Applications

GIS is a popular method used to observe spatial and attribute data of events and analyse hotspots (Erdogan et al. 2008). The GIS platform has the feature to combine many different databases (Anderson 2009). The simplest use of GIS for accident analysis is to examine the spatial characteristics of the accident areas (Steenberghen et al. 2004; Uğurlu et al. 2015b). Spatial analysis in GIS is conducted using 3 methods: point density analysis, linear density analysis and Kernel Density Analysis (Bolstad 2005). The data to be examined with GIS must be either discrete or linear. Since the data in this study is discrete, it is possible to perform density analyses with KDE or point density estimation. KDE is used to estimate continuous density surfaces using a number of sample positions (Cizek et al. 2005; Xie and Yan 2008; Krisp et al. 2009). KDE has widespread use since it has a mathematically flexible structure. KDE is preferred for use here since it is necessary to obtain continuous density surfaces by using the available point data.

In this study, the KDE method was used in conjunction with the GIS ArcMap 10.5 software for the spatial analysis of 33 tanker accidents that occurred in the IS. Initially, accidents are located on the IS map, point by point as shown in Figure 1. Then the required bandwidth and search radius were determined for the KDE application. There are two important parameters that can affect the outcome of the KDE: bandwidth and cell size (Anderson 2009; Prasannakumar et al. 2011). Choosing the optimum bandwidth is a critical step (Jones et. al 1996; Goldsmith et. al. 1999; Fotheringham et. al. 2000; Anderson 2009) as bandwidth selection will affect the outcome of "dense areas". If the bandwidth is chosen too high, non-dense areas will also come out with high density. If the bandwidth is chosen too small, then "hot points" will be detected, not "dense areas" (Silverman 1986; Exchange 2020). In both cases, the application of KDE will give erroneous results, and this will lead to incorrect implications. Therefore, in this study, the optimum bandwidth selection has been made by considering the density of the data and the distribution characteristic on the map.

Since the IS is a narrow waterway, in order to determine the bandwidth and search radius of Kernel areas optimally, trials were conducted in the ranges of (0.2°×0.2°), (0.1°×0.1°), (0.05°×0.05°), (0.035°×0.035°), (0.03°×0.03°) and (0.025°×0.025°). The optimum Kernel bandwidth and search radius was set at 0.035°×0.035°, considering the geographical structure of the IS, the location of the sectors, the prevailing currents and winds, and the distribution of accident data. The high-density areas are divided into five classifications (Very High, High, Moderate, Low, and Very Low) depending on the value of the numerical value of Kernel densities. As a result of the application, a risk map for tanker accidents for the IS was obtained, as shown in Figure 2.

Figure 1. Point distribution map of tanker accidents in Istanbul Strait

Figure 2. Kernel density map of tanker accidents in Istanbul Strait

It can be seen in Figure 2 that there are 4 very high-density areas and 1 high-density area located in Sector Kadıköy, which cover the areas of anchorage A (Yenikapı), anchorage C (Ataköy), anchorage F (Kartal), and the southern entrance (Ahırkapı-Kızkulesi). In these areas, collisions and groundings are the most common accident types with 6 and 4 accidents, respectively. In the Kandilli Sector, the Kandilli turning point, which is the sharpest turn in the region, was determined as a very high (1 area) density sea area. The most common types of accidents in this region are grounding (1 accident) and contact (2 accidents).

2.2.2. GNOME Applications

GNOME software is an effective tool frequently used by local authorities and researchers, of coastal countries, to create oil spill models within electronic maps containing coastal model and hydrodynamic data (currents, tides, wind, *etc*.), to plan response operations (Beegle-Krause 1999; Farzingohar et al. 2011; Cheng et al. 2014; Prasad et al. 2014).

In this study, oil spill modelling was carried out for the sea areas where tanker accidents occur frequently in the IS (very high-density areas). According to the Kernel density analysis results, five very high-density areas have been identified in the IS. The GNOME software was utilised to model 5 separate spill scenarios, all in different locations, as shown in Table 1. However, the following parameters were kept consistent across the 5 scenarios: i) current direction, ii) wind direction, iii) period (72 hours), and iv) the volume of the oil spill (5,000 MT).

In all scenarios, a leak of 5,000 MT was entered into the GNOME software. As a result, 4,930 MT of crude oil was released to the environment in all scenarios. After the first 72 hours, 1,834 MT of this crude oil had evaporated or dispersed. In the South-bound entrance (Ahırkapı-Kızkulesi), in scenarios of Anchorage area A (Ataköy) and Anchorage area C (Yeniköy), 3,096 MT of crude oil reached the shore. In the Kandilli scenario, 3,091 MT of crude oil reached the shore, and 5 MT remained floating. In the Anchorage area F (Kartal) scenario, 2,968 MT of crude oil reached the shore, and 128 MT remained floating.

Table 1. Details of the scenarios used in Istanbul Strait oil spill modelling

2.2.3. Istanbul Strait Prevailing Current and Wind Directions

There are 4 types of currents in the IS, these are: surface (top), deep (bottom), vortex and Orkoz (reverse current) as shown in Figure 3 (Ingerslev 2005; Pizon 2020; SWAN 2020). Similarly, the water level of the Black Sea is 40 cm higher than the one of the Marmara Sea. As the Black Sea is at a slightly higher altitude than the Marmara, the general direction of the surface currents is from the Black Sea to the Marmara Sea. The deep current is formed due to the salinity difference and flows in the opposite direction to the surface current. Since Marmara has a higher salinity than the Black Sea, bottom currents generally flow from Marmara to the Black Sea (Ulusçu et al. 2009). Due to the curved coastline, vortexes occur against the mainstream in the IS and are shown as "counter currents" in Figure 3. Southern winds and especially the lodos sometimes affect sea traffic negatively in the IS (Aydogdu et al. 2012). These winds accumulate the waters of the Marmara Sea to the north and raise them to half a meter at the south entrance of the IS. In this case, the current regime changes and a reverse current called Orkoz occurs on the surface (Figure 3).

Figure 3. General view of current directions in the Istanbul Strait (Pizon 2020)

2.3. *Aliivibrio fischeri* Luminescent Bacteria Toxicity Test (Microtox® Acute Toxicity Test)

The main objective of the study is to explain the potential acute toxic effects of oil transported to the marine ecosystem in regions where tanker ship accidents are highly concentrated. Following the outline of accident density in different regions, the negative effects of oil, and derivative substances carried by tankers, on the coastal area can be determined. *Aliivibrio fischeri* luminescent bacteria toxicity test (Microtox 1992) experiment was used to demonstrate this toxic effect. Based on the scenarios analysed in this research, the goal is to determine the areas in the IS that can be affected by oil pollution toxicity.

In the 29th Scientific Group meeting held by IMO the Microtox® acute toxicity test was put on the agenda under the heading "Waste Assessment Guidance: Application of Biological Assessment Techniques" (IMO 2006). Its use and standardization have been accepted by many countries especially in the sea sediment region (Maranho et al. 2015). However, the main point to note is that due to the low solubility of oil and its derivatives, it cannot be tested alone in bioassays. To *Aliivibrio fischeri* luminescent bacteria toxicity test, the toxicity of waterinsoluble organics (for example crude oil and its derivatives) using the Microtox® system required a versatile and low-toxicity solvent carrier. Dutka and Kwan found that dimethyl sulfoxide (DMSO) at a 1% concentration was not toxic to the various organisms used in a battery of screening tests, including the Microtox® acute toxicity test, nor were any synergistic effects noted between toxicants and 1% DMSO (Wise 1994). Therefore, with the help of solvent (DMSO), crude oil and its derivatives should be transferred to the liquid phase. However, since there are not any naturally occurring extra strong solvents in the study region, the crude oil sample taken for this research was studied without using solvents. Thus, care has been taken to establish the natural conditions in determining the toxic effect of crude oil in surface waters.

The reagent is a freeze-dried preparation of a specially selected strain of the marine bacterium *Aliivibrio fischeri* (NRRL number B-11177). A vial of reagent contains roughly one hundred million test organisms. Test organisms were freeze-dried by using the rehydration method by the authorized company, and freeze-dried bacteria were supplied by Azur Environmental. According to the Microtox® acute toxicity test procedure (Microtox 1992), a 10 µl bacterial culture was exposed to a 500 µl sample. All samples were adjusted to 2.0% salinity (Sodium Chloride-NaCl) through the addition of an osmotic adjusting solution to maintain the appropriate osmotic environment for the bioluminescence bacteria. During the measurements, a negative control known to be non-toxic, and a positive control known to be very toxic was used. For this purpose, a blank sample with no toxicant (negative control) was used to correct the time-dependent change in the light production of the bioluminescence bacteria (Mowat and Bundy 2002). And formaldehyde, known to be very toxic, was preferred to verify as a positive control (Sönmez and Sivri 2016). The difference in light output of the blank control and toxic sample is based on the bioluminescence effect of the organism. After the bacteria were exposed to the sample, light measurements were made at certain intervals (5, 15 and 30 minutes). The median effective concentration (EC_{50}) is the concentration of a substance in an environmental medium expected to produce a certain effect in 50% of test organisms in a given population under a defined set of conditions. The values recorded with the Microtox® Omni software are given as EC_{50} also by using the same software. The results of all exposure times (5^{th}, 15^{th}, and 30^{th} minutes) were statistically evaluated with Statistical Package for the Social Sciences (SPSS) 20 (IBM 2013).

3. Results and Discussion

Prior to examining the results of the oil spills and toxicity, the causes of accidents in marine areas where accidents occurred frequently (Figures 1 and 2) have been revealed. It is useful to understand the potential causes of accidents in risky areas, for planning sea operations (crossing, anchoring) in this region as well as for future safety analysis studies. The IS is one of the narrowest and most congested waterways in the world, with an average of 40,000-50,000 ships passing through per year, thus, accidents can occur frequently. According to the KAIK and Global Integrated Shipping Information System (GISIS) databases, a total of 238 sea accidents occurred in the IS between 2003 and 2018 (KAIK 2018; GISIS 2019). Among these accidents, it was found that contact, collision, grounding and sinking are sensitive to environmental conditions. Environmental conditions include factors that cannot be or may be partially controlled by the operators onboard, such as the type of navigation, the ship's position, weather, and visibility restrictions. Environmental factors play a complementary role in human error events, which can lead to accidents. Every marine incident needs necessary environmental conditions in order to develop into an accident (Uğurlu et al. 2020). Collision, contact, grounding and sinking accidents on the IS, and other narrow waterways, are sensitive to location and environmental conditions. In narrow waterways, accidents in these categories demonstrate clustering at specific locations. Certainly, there is no homogeneous distribution of accidents in narrow waterways, and the results of many studies in the literature provide some verification to this claim (Pelot and Plummer 2010; Giziakis et al. 2013; Acharya et al. 2017). In the light of the studies in the literature and the accident reports in the outlined databases, it is possible to list the factors that play a role in the formation of accidents in the IS, and these factors are presented in Table 2 (Akten 2004; Arslan and Turan 2009; Aydogdu 2014; Uğurlu et al. 2016).

Table 2. Factors involved in the occurrence of accidents in the Istanbul Strait

3.1. Results of the Oil Spill Scenarios

In the first scenario, crude oil spill modelling was conducted in the very high-density area (Figure 2) near the Anadolu Hisarı turning point in Sector Kandilli using GNOME software as shown in Figure 4. The oil reached the shore within 30 minutes due to the narrow structure of the region and the strong current. Half an hour after the spillage, oil pollution affected a 500-meter section of the Bebek-Arnavutköy coast. Due to the northerly wind and southerly current, 4 hours after the spillage, a cumulative 2,000-2,500-meter stretch of coastline at Vaniköy, Kuleli, Çengelköy and Beylerbeyi was affected by oil pollution. If there is no intervention, the total length of the coastline that will be affected by the pollution - after 72 hours has been observed to be 7,000-7,500 meters (Cape of Aşiyan, Bebek, Arnavutköy, Beşiktaş Coastline) (Figure 4).

In the second scenario, crude oil spillage modelling was performed in the Istanbul Anchorage A (Ataköy) area (Figure 2), which is located in Sector Kadıköy, with a very high Kernel density as shown in Figure 5. The spillage spread over the sea surface for the first 24 hours, as the stream is south-westerly, and the wind is northerly. The first contact point of the spillage with the coastline is the beaches of Beylikdüzü (Port of Ambarlı) (after 30 hours). After 48 hours and in the absence of intervention, a total of 25 km of coastline was contaminated, including 9,000 m of the Beylikdüzü coastline, the whole of Büyükçekmece Bay (10,000 m) and part of the Büyükçekmece coastline (6,000 m) after 72 hours, the total length of the coastline (between Yeşilköy and Büyükçekmece) that was affected by oil pollution reached 40 km (Figure 5).

Figure 4. Kandilli area oil spill distribution model

Figure 5. Anchorage area A (Ataköy) oil spill distribution model

In the third scenario, crude oil spillage modelling was applied to the third very high-density Istanbul Anchorage C (Yenikapı) area (Figure 2) located in Sector Kadıköy -. The spillage spread over the –sea surface for the first 30 hours as the surface current is south-westerly, and the wind is northerly. After 32 hours the pollution reached the coastline at the Beylikdüzü coast/Port of Ambarlı. After 36 hours, the oil pollution extended across a 9,000m stretch of coastline from Avcılar to Beylikdüzü. In the absence of intervention, almost all the Avcılar-Beylikdüzü coastline (14 km) was affected by crude oil pollution after 48 hours due to the effect of current and wind.

In the fourth scenario, crude oil spillage modelling was implemented in the fourth very high-density area at the Istanbul South-bound entrance (Ahırkapı-Kızkulesi), which is the entry point on the Black Sea side of the IS, within the sector Kadıköy as shown in Figure 2. Since the current in the region is south/south-westerly and the wind is north/north-westerly, the pollution spread over the sea surface for 36 hours and moved on the sea surface about 35 km away (Beylikdüzü coast) from the first discharge point. The first point of coastal contact was after 39 hours at Beylikdüzü/Yakuplu (40° 58.3'N - 028° 41.8'E). After 48 hours, and without intervention, approximately 13 km of the Avcılar-Beylikdüzü coastline was affected by crude oil pollution. After 72 hours, the entire Büyükçekmece Bay (10 km) and the entire Avcılar-Beylikdüzü coastline (14 km) were contaminated with crude oil.

In the fifth and final scenario, crude oil spillage modelling was applied to the very high-density Istanbul Anchorage F (Kartal) area (Figure 2) located in the southeast of the sector Kadıköy, as shown by Figure 6. In the first 48 hours, the spillage spread to a large extent on the sea surface, since the current is south-westerly, and the wind is north/north-easterly. The direction of the current became southeast/easterly after 48 hours and the direction of the wind became southerly. This situation accelerated the movement of the spillage towards the coastline, subsequently the pollution first reached the coastline after the 52 hours, stretching between Sedef Island (400 m) and Büyükada (3,000 m) beaches. After 72 hours, oil pollution had affected the entire south and southeast coasts of Kınalıada (1,900 m), Burgazadası (2,500 m), Heybeliada (2,500 m), Büyükada (6,000 m) and Sakız (Chios) Island (1,800 m). In addition, the pollution affected 6,000 m of the Kartal coastline, 7,000 m of the Pendik coastline and the entire Tuzla Bay coastline (8,000 m), as shown by Figure 6.

Figure 6. Anchorage area F (Kartal) oil spill distribution model

Once the five scenarios were evaluated, it was seen that the worst scenario occurred as a result of spillage in the Istanbul Anchorage F (Kartal) area. The reason that the coastal structure of the Kartal anchorage area is affected more than other areas is the presence of islands where the current and wind have a variable structure compared to other regions. This has caused both the islands and the coastline to be affected by the oil spillage.

The oil spill analysis results have revealed that a rapid response is the most important step in preventing environmental disasters when an accident occurs. To shorten the response time, in addition to the equipment and personnel training onboard, an "Emergency Response Land Station" should be established closer to the very-high density areas. The Turkish General Directorate of Coastal Safety is planning to establish emergency response land stations at 19 different locations along the coastline of Turkey (KEGM 2020). It is planned to deploy one of these stations at Tuzla, which will serve the IS and the Marmara Sea. It is estimated that Tuzla Station will respond quickly to possible pollution in the Marmara Sea. However, the station will shorten the response time to an oil pollution incident if it is placed in another area, which is equidistant to both sides (east-west) of the IS and close to the Kartal Anchorage area, such as Maltepe instead of Tuzla. In this proposed situation, in any scenario, except for the one in Kandilli (Figure 4), oil will not reach the coast in the first 6-12 hours and the pollution spread can be controlled. The Kandilli scenario in this study revealed the necessity to establish an emergency response station in the IS. The strong current and narrow geographical structure of the IS showed that pollution can reach the shore in a very short period of time; in this case, 30 minutes (Figure 4). The response time can be shortened in events that will occur throughout the IS by establishing an emergency response station at a point overlooking the whole Istanbul Strait, such as Beykoz (41° 07.31'N-029° 05.71'E) and Sarıyer (41° 09.36'N-029° 02.34'E), etc. Thus, the magnitude of the damage, permanent contamination and negative environmental impact can be reduced.

3.2. Results of Acute Toxicity of Crude Oil to *Aliivibrio fischeri*

Following the scenarios, the study was carried out in two stages in order to determine the potentially toxic effects of petroleum and its derivatives in natural waters in the regions where accident-prone areas are determined. In the first stage, the points to be considered in determining the toxic levels of crude oil were evaluated. In the study conducted by Ateş (2018), it is stated that the fingerprint of each oil is different since the crude oil has a characteristic feature depending on where it was extracted, thus its chemical structure is unique. It is also known that the toxicity of low density (high °API) oil is higher due to the low molecular weight hydrocarbons in its chemical structure (Morales-Bautista et al. 2013). In the acute toxicity test of the crude oil sample in this study, the concentration intervals in which *Aliivibrio fischeri* can respond to the crude oil have been determined since *Aliivibrio fischeri* do not respond at high concentrations (when the light emission cannot be read). The results are presented as (Coleman and Qureshi 1985; Al Muzaini et al. 1997):

- If EC_{50} (% or mg / L) is smaller than 25, then it is "*very toxic*".
- If EC_{50} (% or mg / L) is 25–50, then it is "*moderately toxic*".
- If EC_{50} (% or mg / L) is 51–75, then it is "*toxic*".
- If EC_{50} (% or mg / L) is 75-99, then it is "*slightly toxic*".
- If EC_{50} (% or mg / L) is larger than 100, then it is "*non-toxic*".

In studies conducted by Eisman et al. (1991), Aruldoss (1996) and Saeed and Beg (2007), Microtox® was used as an analyser in *Aliivibrio fischeri* luminescent bacteria toxicity test. In these studies, it is seen that oil is "*toxic*". Furthermore, different concentrations of crude oil were studied with samples taken from the surface waters of the IS. The aim is to improve the accuracy of the results of these simulations with the original surface water samples taken from the regions where spills have been simulated. Accordingly, in the 1:125,000 dilutions of the crude oil sample with seawater, EC_{50} values were calculated for all exposure times (5, 15 and

30 minutes). The results were 24.41, 18.34, 21.39 mg/L, respectively, thus the samples are deemed to be very toxic. The results obtained at 1:150,000 dilutions were 39.95, 40.04 and 37.32 mg/L, respectively, thus the samples were still found to be toxic. Dilutions continued and at the end of the 30th minute, a 99.7 mg/L solution was found at 1:175,000 dilutions (slightly toxic). Continually, after analysing the 1:200,000 dilutions with the same method, the samples became non-toxic (> 100 mg / L) for all exposure times (5, 15 and 30 minutes). In summary, when crude oil is poured into the sea, only 1:200,000 dilutions of oil with seawater will render the pollution non-toxic. All results were compared with the positive control as shown in Figure 7.

Figure 7. EC_{50} (mg/L) values by exposure times

It was determined that no statistically significant difference was found between 5-, 15- and 30-minute intervals. A period of 5 minutes has been deemed long enough to form an idea about toxicity ($p > 0.05$). Therefore, the 5-minute exposure time can be given for the rapid detection of petroleum contamination. A bioluminescence test (BioTox™assay) can be applied as a rapid pre-screening test for toxicity evaluation of spilled oil in the beach sand and the sediment (Tosun, 2007). It is known that eggs and larvae of aquatic life forms and sediments are more sensitive to this type of pollutant than other creatures. Animals that live at the bottom of the sea, such as crabs, lobsters, and shrimps, are more susceptible to oil contamination. These are affected by oil concentrations of 1-10 parts per million (ppm). Bivalve crustaceans and some other species, such as mussels, are known to be sensitive to oil at 5-50 ppm, with marine plants sensitive at 10-100 ppm (Demiray 2006).

Petroleum-derived wastes in international waterways, such as the Turkish Straits, which serve as an ecological and/or biological corridor, negatively affect the water quality and coastal area. When all the scenarios and toxicity results are evaluated together, it is possible to see the toxic effect of crude oil even at the last point that crude oil can reach. It is seen that if the oil is diluted with sea water (at a ratio of 1:200,000), its toxic effect will decrease, but its chronic effect may continue. Such results would consider not only oil dispersion but also ecological impacts, and connections to human health and economic impacts. These results could address questions such as what the worst-case disaster would be, what pre- and post-disaster interventions are critical, and what interventions are robust in reducing losses over a broad range of possible spill events.

4. Conclusion

In the study by using the Kernel density analysis, high-density areas where tanker accidents were concentrated in the IS were identified and risk maps were presented (Figures 1 and 2). These maps can be used as decision support aids in selecting locations of marine pollution response stations and preparing response strategies. Crude oil spill modelling was carried out on five scenarios in areas identified as very high density in risk maps, by using GNOME software. As a result, in the event of spillage of a 5,000MT crude oil spill, it was determined that there would be a destructive trail along a 10-15 km stretch of coastline within the first 72 hours, without intervention. The strong and variable surface currents and wind in the IS and Marmara Sea (Figure 3) are the main triggers of this spread (Figures 4-6).

In the ecological evaluation conducted with the results of this study, it can be stated that the species that live in areas that are toxic due to crude oil spills may be directly and/or indirectly affected. The negative consequences of this effect could be seen directly on many different living creatures, such as phytoplanktonic organisms and zooplanktonic species. It is worth noting that, this region is a bird migration and habitat route, and the area also contains numerous species of fish. Furthermore, some species with low tolerance, affected by environmental conditions are included in the IUCN RedList. It can be scientifically observed that all species in the food chain, from the phytoplankton to the highest trophic level, are affected by oil spill pollution. The damage to the ecosystem in each accident is a subject of a separate investigation, thus maximum efforts should be made to prevent possible damage and pollution to the marine ecosystem.

In the five scenarios in the study, the amount of oil spilled, the duration of dispersion without intervention, and the atmospheric conditions in which the accident occurred remained constant. The main reason for this is to reveal how the scale of the disaster changes in relation to the change of the accident position in the same weather and sea conditions, with the same amount of spillage over the same time. However, in this study, the effect of different seasons and different spillage amounts on the spread of the spills were not investigated. In the future, different volumes of oil spills can be made at certain points of IS and leakage can be modelled at different current and wind intensities in variable seasons. These models can serve as a reference for coastal safety and ship salvage authorities when developing contingency plans.

The results of this study may serve as a reference for coastal state authorities to develop emergency response plans. Having this valuable knowledge of where high-risk accidents are most concentrated, which areas can be affected by the pollution, the duration of the pollution effects, and the distance between the areas, will help determine the number of intervention stations to be installed, their locations, and equipment to be installed to the stations. Moreover, effective monitoring is essential, and in the monitoring of coastal ecosystems, it may be appropriate to use Remotely Operated Vehicles (ROVs) in a successful coastal zone protection plan with conventional environmental technologies and toxicity tests. It is important to monitor the coastal areas regularly to determine the current status and take appropriate actions rapidly to protect coastal areas.

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Table 1. Details of the scenarios used in Istanbul Strait oil spill modelling

Very-High Accident Density Areas	Spilled Substance	Spillage Coordinates	Spillage Size (metric tons)	Duration (h)
Kandilli	Crude oil	41º 04,3' N - 029º 02,9' E	5,000	72
Anchorage area A (Yenikapı)	Crude oil	40º 58,7' N - 028º 57,0' E	5,000	72
Anchorage area C (Ataköy)	Crude oil	40º 56,5' N - 028º 50,5' E	5,000	72
South-bound entrance (Ahırkapı-Kızkulesi)	Crude oil	40º 59,7' N - 028º 59,6' E	5,000	72
Kartal anchorage area	Crude oil	40º 52,0' N - 029º 11,7' E	5,000	72

Table 2. Factors involved in the occurrence of accidents in the Istanbul Strait

Factors	Kandilli	Anchorage area A (Yenikapı)	Anchorage area C (Ataköy)	South-bound entrance (Ahırkapı-Kızkulesi)	Kartal
Heavy weather and sea conditions		X	X		X
Strong current	X			X	
Sharp turns	X			X	
Narrow fairway	X			X	
Excessive shore lighting	X	X	X	X	
Local traffic		X		X	
Faulty manoeuvring	X	X	X	X	X
Engine failure	X	X	X	X	X
Dredging anchor		X	X		X
Faulty navigation	X			X	
Dense fog		X	X		X
Rudder failure	X			X	
Night	X	X	X	X	
Unsafe speed	X	X	X	X	X
Inadequate lookout		X	X		X
Dense traffic		X	X		X
Shallow water		X	X		
Inadequacy of anchorage areas		X	X		X

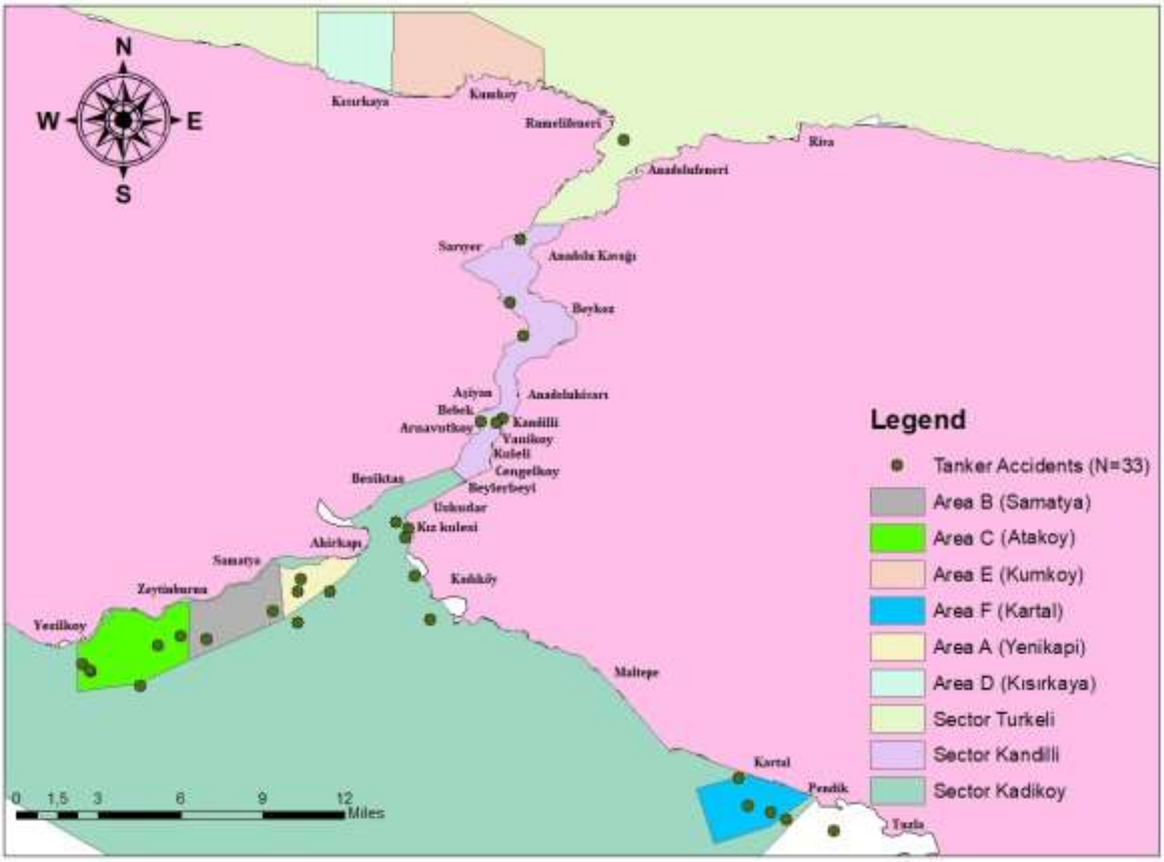

Figure 1. Point distribution map of tanker accidents in the Istanbul Strait

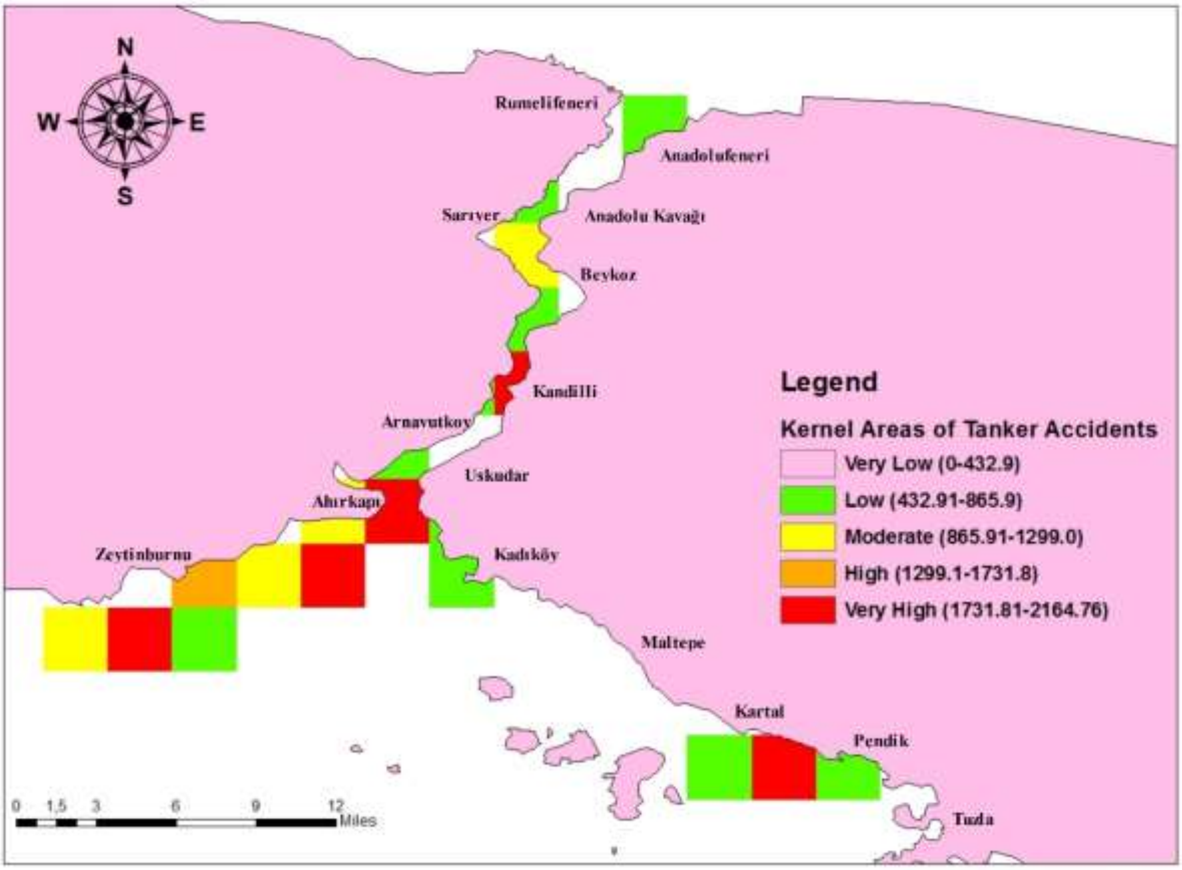

Figure 2. Istanbul Strait tanker accident risk map (Kernel density map)

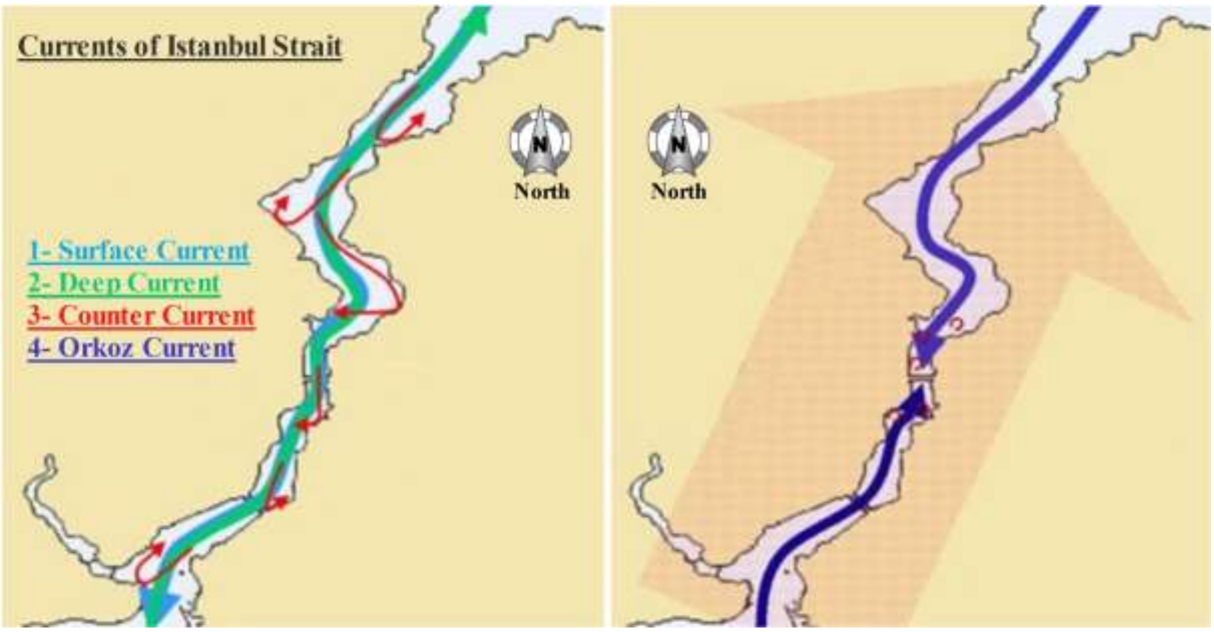

Figure 3. General view of current directions in the Istanbul Strait (Pizon, 2020)

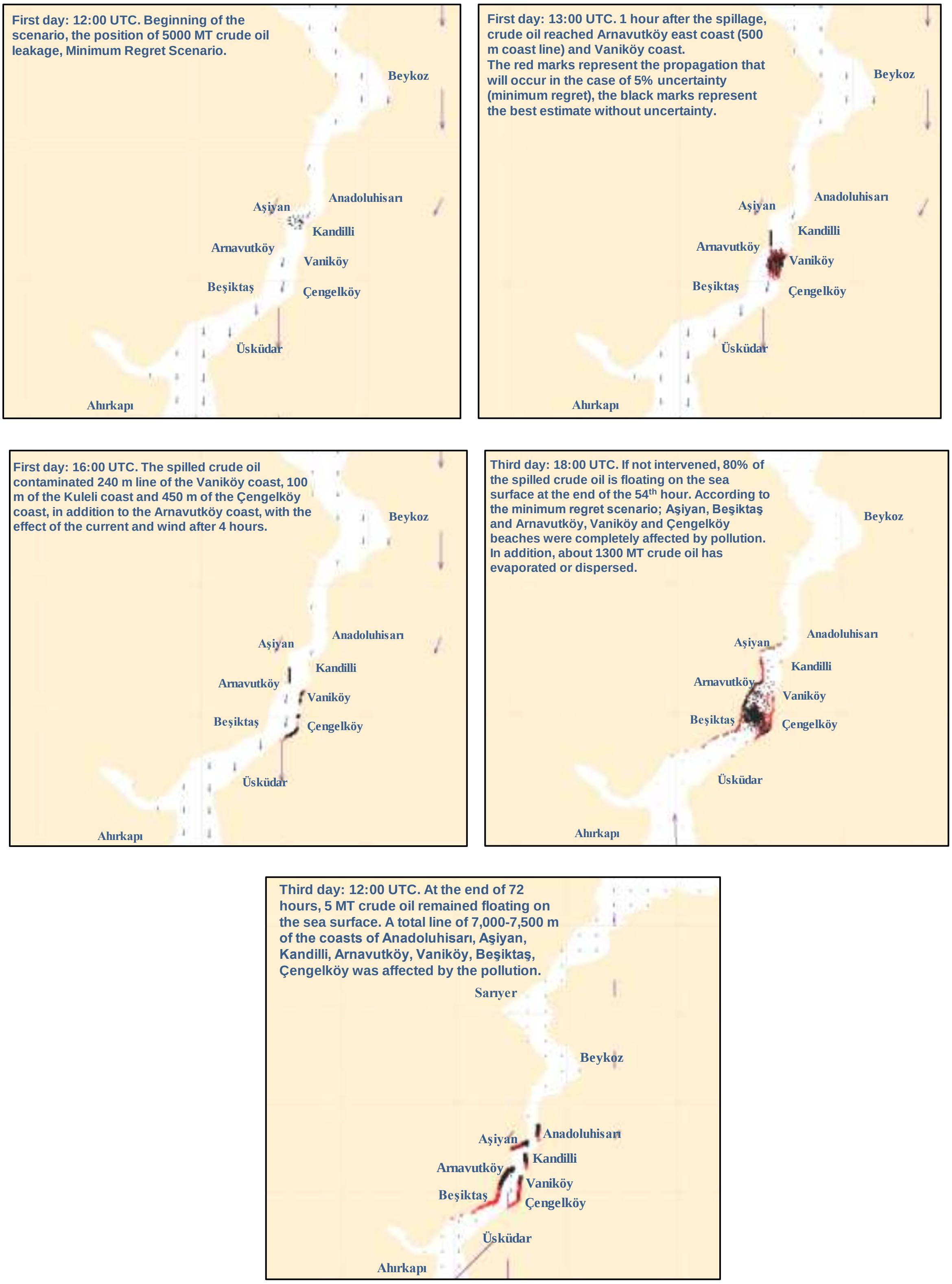

Figure 4. Kandilli area oil spill distribution model

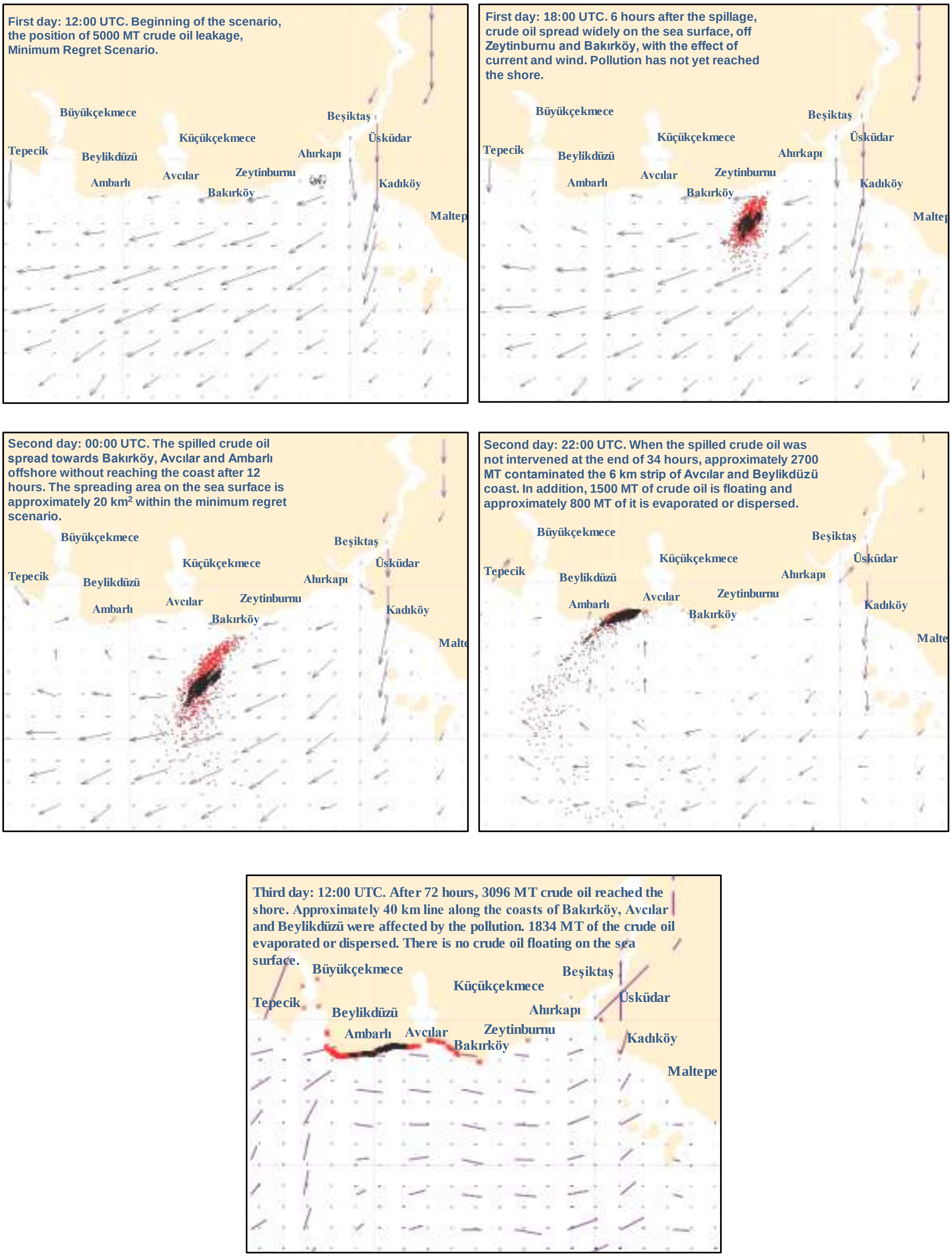

Figure 5. Anchorage area A (Yenikapı) oil spill distribution model

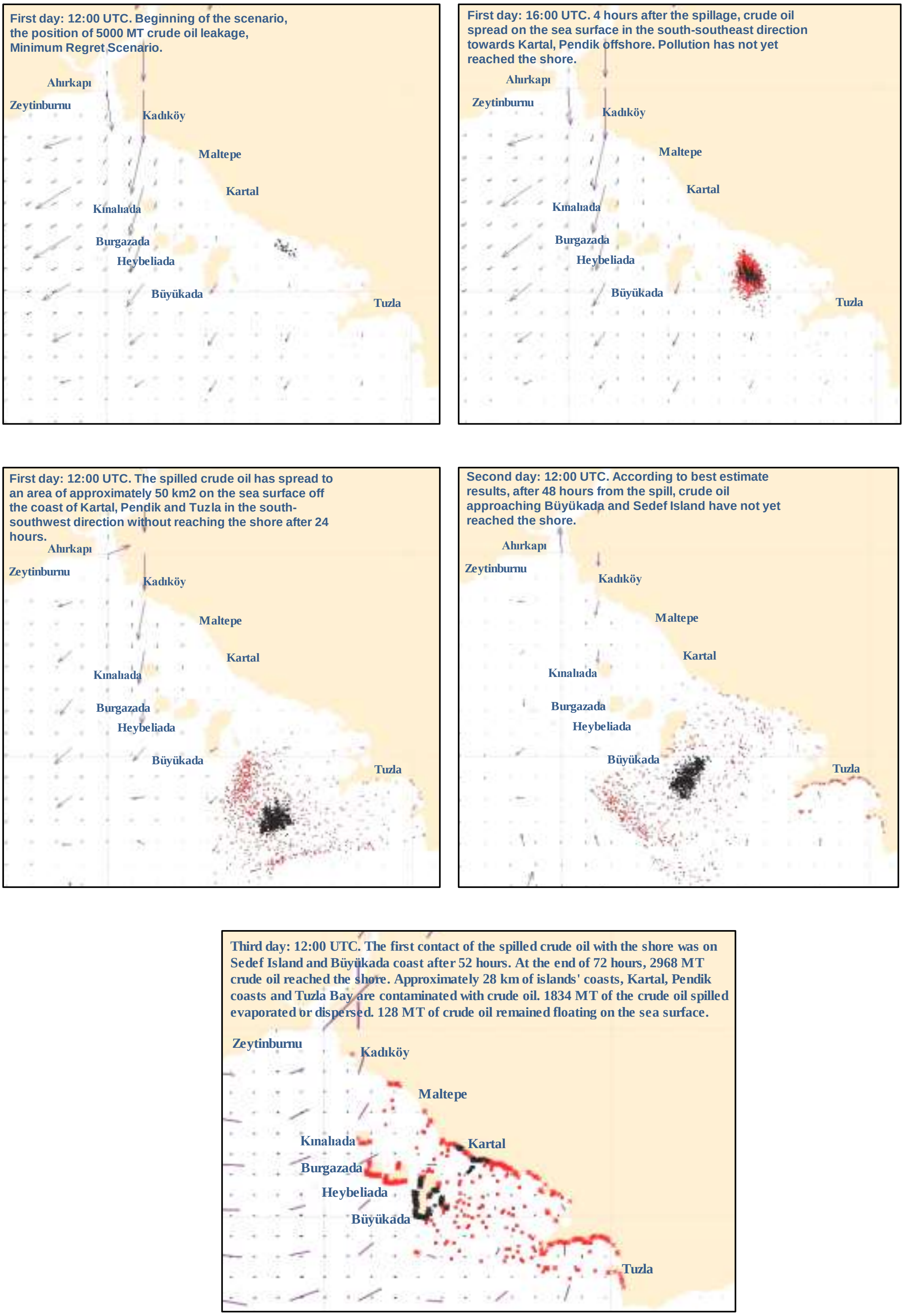

Figure 6. Anchorage area F (Kartal) oil spill distribution model

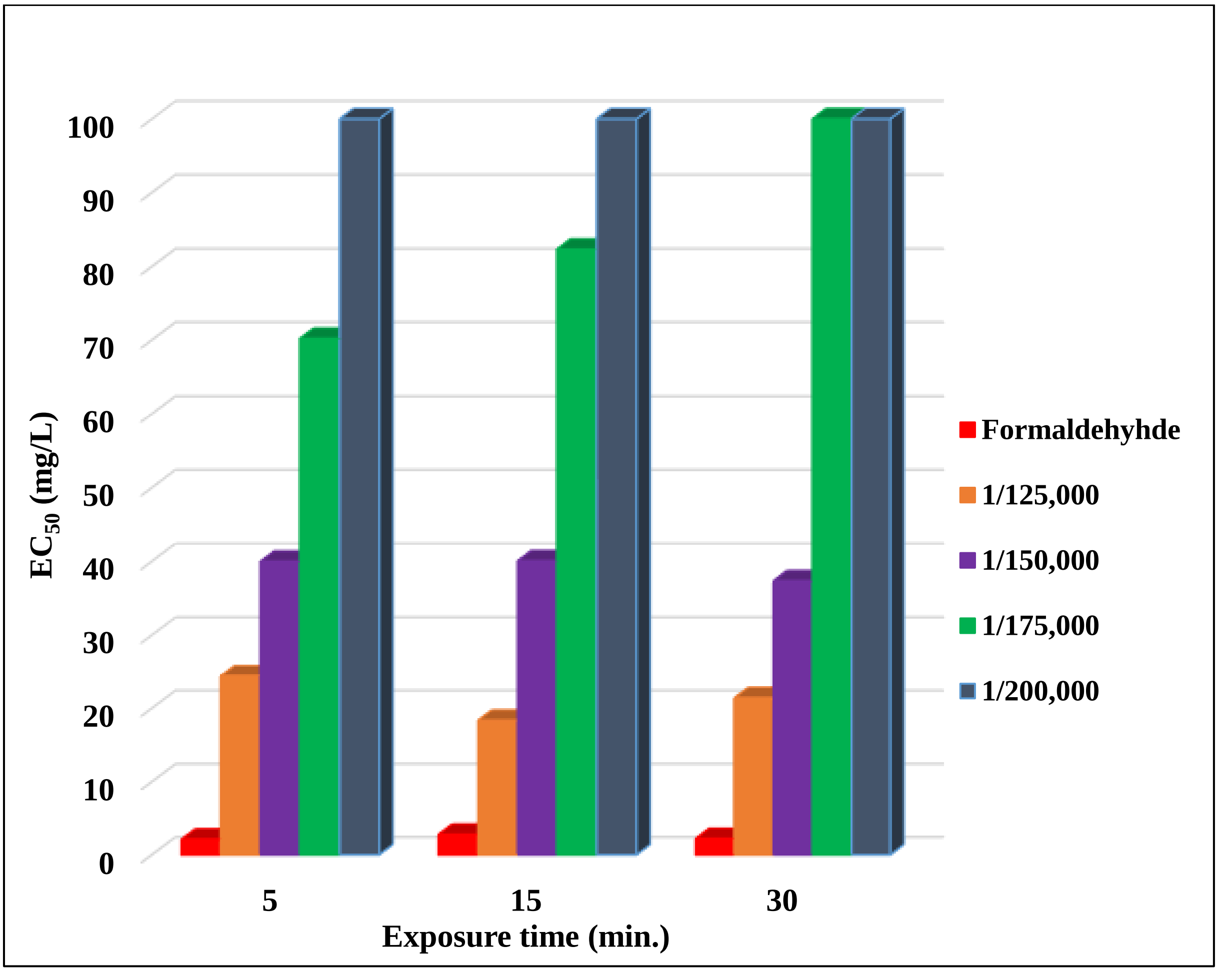

Figure 7. EC_{50} (mg/L) values by exposure times