Management of oil spill contamination in the Gulf of Patras caused by an accidental subsea blowout

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ABSTRACT

A methodology is presented and applied to assess the oil contamination probability in the Gulf of Patras and the environmental impacts on the environmentally sensitive area of Mesolongi – Aitoliko coastal lagoons, and to examine the effectiveness of response systems. The procedure consists of the following steps: (1) Determination of the computational domain and the main areas of interest, (2) determination of the drilling sites and oil release characteristics, (3) selection of the simulation periods and collection of environmental data, (4) identification of the species of interest and their characteristics, (5) performance of stochastic calculations and oil contamination probability analysis, (6) determination of the worst-cases, (7) determination of the characteristics of response systems, (8) performance of deterministic calculations, and (9) assessment of the impact of oil spill in the areas of interest. Stochastic calculations that were performed for three typical seasonal weather variations of the year 2015, three oil release sites and specific oil characteristics, showed that there is a considerable probability of oil pollution that reaches 30% in the Mesolongi – Aitoliko lagoons. Based on a simplified approach regarding the characteristic of the sensitive birds and fish in the lagoons, deterministic calculations showed that 78-90% of the bird population and 2-4 % of the fish population are expected to be contaminated in the case of an oil spill without any intervention. The use of dispersants reduced the amount of stranded oil by approximately 16-21 % and the contaminated bird population of the lagoons to approximately 70 %; however, the affected fish population increased to 6-8.5 % due to the higher oil concentration in the water column. Mechanical recovery with skimmers "cleaned" almost 10 % of the released oil quantity, but it did not have any noticeable effect on the stranded oil and the impacted bird and fish populations.

Capsule: The oil pollution probability in the Gulf of Patras and the environmental impacts on the nearby coastal lagoons are assessed and the effectiveness of oil spill response systems are examined.

Keywords: oil spill contamination; oil spill modelling; oil contamination probability; subsea blowout; Mesolongi – Aitoliko coastal lagoons

1. Introduction

The Gulf of Patras is a part of the Ionian system, which is one of the three major petroleum systems in Western Greece (Karakitsios, 2013). Preliminary seismic surveys in the Gulf of Patras have detected interesting oil prone geological structures with the recoverable reserves to be estimated around 200 MMbbls (http://www.ypeka.gr/Default.aspx?tabid=766&locale=en-US&language=el-GR, last access 3 July 2017). The final and detailed seismic survey and exploitation is expected to start soon by the group of companies that undertook the relevant contract (EU, 2015). Since the drilling sites are close to high sensitivity and environmentally protected coastal areas, such as the Mesolongi and Aitoliko lagoons, an oil spill release due to a potential accident may cause significant environmental damages (Beyer et al., 2016; Goovaerts et al., 2016; Hester et al., 2016). Therefore, it is important to assess a priori these damages and determine proper oil spill response methods to manage (avoid or reduce) them. This assessment can be achieved via an Oil Spill Model (OSM) that determines the transient behavior of an oil spill, i.e. its trajectory and corresponding concentrations, from which we can estimate the contamination probability and arrival time in the areas of interest (Hellenic Center of Marine Research (HCMR), 2012), and the effect of applied oil spill response systems.

There exist various OSMs in the literature; see Spaulding (2017) for a review of the state of the art in OSMs from 2000 to present, which describe the behavior of an oil slick that may be caused by subsea blowouts (Socolofsky et al., 2015) or surface accidents (Papadonikolaki et al., 2014; El-Fadel et al., 2012). Generally, the frequency of blowout spills is lower than that of surface spills; however, the total environmental risk from blowouts is higher due to the (i) larger quantities of released oil (Eckle et al., 2012), and (ii) higher pressures involved that make them very difficult to control (Lamine and Xiong, 2013). Since the oil slick behavior depends strongly on the local weather and ocean circulation conditions, we usually obtain the required data (to be used as input to the OSM) from a weather model (Kallos et al., 1997) and an ocean circulation model (Blumberg and Mellor, 1987) that are applicable in the specific area of study. To produce realistic results, we define reasonable oil spill scenario characteristics for the (i) spill location, (ii) release duration, (iii) flow rate and (iv) crude oil type; we can select these data based on past and well-studied incidents, such as the Deepwater Horizon blowout (McNutt et al., 2012).

Generally, there are two main types of applications of OSMs. The first type deals with the determination of the contamination probability maps due to an oil slick in the areas of interest; to produce accurate maps, we need to take into account the stochastic nature of the oil slick behavior via the definition of multiple periods (or seasons) of study per year and multiple spill locations to perform the so-called “stochastic” simulations for a sufficient period of time (Alves et al., 2015; De Dominicis et al., 2013; Goldman et al., 2015; Melaku Canu et al., 2015). In the second type of application, we study the detailed behavioral characteristics of a specific oil spill and/or the effectiveness of the available oil spill response methods (Alves et al., 2016), but also for model inter-comparison purposes (Socolofsky et al., 2015). In such cases, we perform the so-called “deterministic” calculations for just one oil spill for a specific period and specific weather and ocean circulation conditions.

In the present work, we apply a modeling methodology that combines stochastic and deterministic oil spill simulations using the oil spill model OSCAR (Daling et al., 1990; Reed et al., 1995a; Reed et al., 1995b; Reed et al., 2000; Reed and Hetland, 2002): (i) to assess the oil contamination probability in the Gulf of Patras and the possible environmental impacts on the Mesolongi – Aitoliko coastal lagoons, and (ii) to examine the effectiveness of the available oil spill response methods; this study is the first regarding oil spill modeling in the Gulf of Patras and the first worldwide that combines stochastic with deterministic simulations.

2. The area of study

We performed oil spill simulations in the 100 km x 97 km area of study, which is shown in Fig.1; it is surrounded by the islands Kefalonia, Ithaki, Zakynthos and Lefkada (not shown in Fig.1) on its western side, and continental Greece on the east. Numerous touristic zones, fisheries and environmentally protected areas are located within the area of study. Significant wetlands include the Strofylia wetland (west coast of Peloponnese), Laganas beach (south coast of Zakynthos island), where the loggerhead sea turtles (Caretta-Caretta) migrate to lay their eggs in summer, the Petalas wetland (west coast of mainland) and the Mesolongi - Aitoliko lagoons (the total area of the lagoons is equal to 170 km^2 and the total volume is equal to approximately 0.17 km^3), which constitute the main focus area for this study. This lagoon system is part of an extensive wetland complex in the northern region of the Gulf of Patras (Fig.1) that is protected under the RAMSAR international convention for wetlands (http://www.ramsar.org/wetland/greece, last access 3 July 2017). The Aitoliko lagoon, to the north, has a mean depth of 12 m and a maximum depth of 33 m (Leftheriotis et al., 2013); its bottom layers are permanently anoxic due to limited water circulation, while occasionally, advection to the surface causes total anoxia, resulting in massive mortality of aquatic organisms (Gianni et al., 2011). The Mesolongi lagoon has a mean depth of 0.5 m, while its maximum depth is approximately 2.5 m (Leftheriotis et al., 2013). Human intervention has altered severely the geomorphological and hydrological features of the Mesolongi-Aitoliko area (Greek Ministry of Environment, 1998), with various effects on biotic and abiotic factors of the ecosystem. However, unique features of estuarine ecosystems, like sand dunes, salt marshes and mudflats, still exist providing shelter to various species. The lagoon is very important for migratory wintering and breeding birds; more than 280 different species have been observed in the area during the year (Greek Ministry of Environment, 1998). Vegetation in the area includes rare and endangered species. Human activities include extensive fishing and fish farming. Fish can generally be divided in those that spend their whole life cycle in the lagoon and those that spawn in the open sea and enter the lagoon to find food and shelter (Nikolaidou et al., 2005).

3. Presentation and application of the methodology

In the present section, we describe and apply the proposed methodology in a series of 9 steps.

Step 1. Determination of the computational domain and the main areas of interest. The computational domain of OSCAR covers the area of study that is shown in Fig.1; we have employed 11 layers in the vertical direction with the following water depths: 0.0-3.0 m, 3.0-8.0 m, 8.0-13.0 m, 13.0-18.0 m, 18.0-25.0 m, 25.0-40.0 m, 40.0-65.0 m, 65.0-115.0 m, 115.0-125.0 m, 225-475.0 m and 475.0-825.0 m, and a horizontal resolution equal to 100 m x 100 m, which resulted in a total number of surface cells that is equal to approximately 10^6 cells. The bathymetry of the area was obtained from the US Navy Digital Bathymetric Data Base (DBDB1) that has a nominal resolution of 0.017 degree, by bilinear interpolation via the application of the ocean circulation model that is briefly described in step 3. The main areas of interest are the environmentally sensitive Mesolongi – Aitoliko coastal lagoons that are also shown in Fig.1.

Step 2. Determination of the drilling sites and the oil release characteristics. Currently, there is no legal framework in Greece for offshore oil drilling activities in the Gulf of Patras; moreover, there is no information on the locations of oil reserves. Therefore, we determined at a preliminary level, the drilling sites A, B and C that are shown in Fig.1 that are away from a buffer zone of 5 km from ship routes, coasts and protected areas. Since the corresponding sea water depths at sites A, B and C are 130 m, 177 m and 70 m, respectively, we expect that the plume of the oil rises fast to the surface without being trapped in the water column. Moreover, since offshore drilling has not started yet, there is no information on the potential blowout and oil characteristics. Therefore, in the calculations, we assumed that the temperature of oil is equal to 60 °C, the diameter of the release is equal to 0.3 m, and the flow rate is equal to 10000 m^3/d; this value of flow rate is reported in the environmental impact study by the Hellenic Center of Marine Research (HCMR, 2012) and is practically equal to the flow rate of the Deepwater Horizon blowout (average flow rate= 8400 m^3/d), but with a much shorter duration of release (McNutt et al., 2012; Zhao et al., 2015). Also, we used the oil characteristics of the Oseberg Blend, a low viscosity (5 cP at 40 °C), light paraffinic oil with API equal to 37.2 and specific gravity equal to 0.839.

The characteristic diameters of the initial oil droplet size distribution were estimated equal to D_{95}=7.8 mm and D_{max}≈11.2 mm, using an algorithm that employs the modified Weber scaling (Johansen et al., 2013), which is based on Hinze (1955), but it also includes additional terms that take into account the oil properties (mainly viscosity), mixed releases of oil and gas and increased release velocity from buoyancy dominated releases; this algorithm was verified through extensive laboratory and basin testing (Brandvik et al., 2013; Brandvik et al., 2017). The duration of release depends on many factors, such as the extent and complication of damage and the availability of personnel and equipment for capping the well; since there is no such information, we assumed a 5-day duration before the well is capped or the blowout is otherwise controlled; subsequently, the total released volume of oil was equal to 50000 m^3 (42236 t).

Step 3. Selection of the simulation periods and collection of the weather and sea current data. We examined a 13-years series of meteorological data, mainly wind conditions (HCMR, 2012), (i) to select year 2015 as being representative for long term trends, and (ii) to define three typical seasonal weather variations in this region that are: (1) spring (15/3-14/5), (2) summer (28/6-27/8), and (3) winter (1/11-31/12). For these periods, we obtained (i) hourly wind data for speed and direction at 10 m using the SKIRON weather forecasting model and (ii) sea currents data from the Southern Adriatic - Northern Ionian Sea 2 (SANI2) circulation model through an OPenDAP (Open-source Project for a Network Data Access Protocol) server; these data were used as input to the OSCAR oil spill model; see steps 5-9.

SKIRON covers the Mediterranean region and part of Central Europe; it was developed by the Atmospheric Modeling and Weather Forecasting Group at the University of Athens within the framework of the projects SKIRON and Mediterranean Dust Experiment (Kallos et al., 1997). SKIRON provides horizontal resolution of 0.05 degree and it is forced via the setting of initial and boundary conditions using the low resolution (0.5 degree) Global Forecast System (GFS) by the National Centers for Environmental Prediction (NCEP).

SANI2 covers the southern Adriatic and the Ionian Sea; it was constructed by the Hellenic Center of Marine Research (HCMR) within the framework of the IONIO project and was validated using field data for the period 2008-2012 in four geographical regions Southern Adriatic, Otranto Strait, Northern Ionian and Southern Ionian (Kassis et al., 2017). SANI2 has a horizontal resolution of 0.02 degree and 25 sigma levels along the vertical with a logarithmic distribution near the surface and the bottom; it is based on the Princeton Ocean model (POM). The SANI2 model is forced with hourly surface fluxes of momentum, heat and water provided by the Poseidon eta high resolution (0.05 degree) regional atmospheric model (Papadopoulos et al., 2002); the lateral boundary conditions for the sea current velocity, temperature, and salinity are imposed from the Mediterranean Monitoring and Forecasting Centre Med-MFC (Clementi et al., 2017) provided by the Copernicus Marine Environment Monitoring Service (CMEMS).

Step 4. Identification of the species of interest and estimation of their characteristics. To assess the environmental damage in the lagoons by a potential oil spill, we need to identify the most important and sensitive species in the areas of interest that are expected to be affected by the oil spill, as well as their tolerance to oil toxicity. Based on the very limited information in the relevant literature, we identified two main species in the areas of interest that are the (Eurasian) Coot (*Fulica Atra*) and the Mediterranean Killifish (*Aphanius Fasciatus*), which is included in the IUCN Red List of Threatened Species (http://www.iucnredlist.org/details/1847/0, last access 3 July 2017).

Coot is an aquatic bird that inhabits still or slow-flowing shallow waters, lakes, lagoons, open marshes and river deltas; it is omnivorous and nests on obstacles protruding from the water. Coot's populations that live in northern Europe and Asia are migratory, whereas those that live in more temperate climates are resident (http://www.birdlife.org/datazone/species/factsheet/22692913, last access 3 July 2017). In Mesolongi, about 15500 wintering individuals have been counted (http://ornithologiki.gr/page_iba.php?aID=92, last access 3 July 2017) during the winter months

(November to February) (http://www.nagref.gr/journals/ethg/images/31/ethg31p4-7.pdf, last access 3 July 2017). To assess the impact of oil spill, we assumed that damage to the Coot may occur, when the oil thickness is higher than 0.01 mm (French-McCay, 2009); this damage is through direct contact with oil that destroys the insulating properties of their plumage, or via oil ingestion that may result in lung, liver and kidney damage, often leading to death (Fitzpatrick et al., 2000). Killifish is a demersal fish that can be found in the coasts of central and eastern Mediterranean; it inhabits shallow and isolated areas, such as lagoons and salt marshes, it can tolerate high salinity and it spends its whole life cycle in shallow waters without migrating in the open sea to spawn (Leonardos and Sinis, 1997). To assess the impact of oil spill on the Killifish, we assumed that oil slick is toxic to the Killfish, when the oil concentration is greater than 10 ppm; this assumption is based on the available Predicted Effect Concentration (PEC) values for demersal species that live in lagoons and the relevant literature; see for example Malins and Hodgins (1981). Due to the lack of any relevant data, we made the simplified assumption that the Coot and the Killifish are uniformly distributed in the surface area and the volume of the lagoons, respectively, throughout the whole year.

Step 5. Performance of stochastic calculations and oil contamination probability analysis. We performed stochastic oil simulations using the oil spill model OSCAR to determine the probability of different areas to be contaminated by oil. OSCAR (Daling et al., 1990; Reed et al., 1995a; Reed et al., 1995b; Reed et al., 2000; Reed and Hetland, 2002) simulates the fate and behavior of oil released at sea either from an instantaneous or a continuous source; it accounts for the weathering processes that affect oil and can be used to assess the environmental impact of an accidental oil release, as well as the effectiveness of various response methods. The following weathering processes are considered in OSCAR: drifting, spreading, evaporation, photo-oxidation, emulsification, natural dispersion, dissolution, degradation, sediment interactions and stranding. Varying weather and sea conditions during a certain time period can thus be considered in order to calculate oil spill probability at specific areas.

OSCAR follows the Lagrangian approach, in which individual oil particles are used to represent the moving oil slick. Initially, particles are released due to subsea blowout forming a near-field plume (Johansen, 2000) that is transferred to the far field driven by the flow field. The particle trajectories are tracked and their properties are calculated as a function of time; Newton’s law of motion and conservation of mass apply directly to each particle. Oil particles are advected by the mean flow velocities (due to tidal and wind driven currents), while they are dispersed due to flow turbulence. In OSCAR, this random dispersion process is modeled via a particle-based algorithm that uses dispersion values (i.e. diffusivities) that are calculated following Reed and Hetland (2002); therefore, two simulations with the same input characteristics are not expected to produce the same result. In the description of particle advection on the sea surface due to windage, the wind drag coefficient is set equal to 3.5 % (Lange and Huehnerfuss, 1978). In the present work, where the area of study is fairly sheltered, we have ignored the effect of waves (Stokes drift), which is expected to be minor. However, in other cases; see for example De Dominicis et al., 2013, the effect of Stokes drift can be important. It is noted, that in some parts of coastal areas of the computational domain of OSCAR,

which are not covered by the hydrodynamic model (SANI2) and thus there are no velocity data, advection is ignored and only wind-induced currents and random dispersion affect the transport of oil particles.
At each timestep of the computations with OSCAR, oil particles are transported via the processes of advection and dispersion, while they undergo a series of weathering processes; these processes transfer mass to the five compartments of the model, which are the atmosphere, the water surface, the water columns, the bottom- sediment, and the shoreline (Reed et al., 1995b). At each model output timestep, the mass balance in terms of tons of oil (t) in each compartment is monitored. A more detailed presentation of the weathering processes is found in Daling et al., 1990; Reed et al., 1995a; Reed et al., 1995b; Reed et al., 2000; Reed and Hetland, 2002), while in (Daling et al., 1997; Daling and Strom, 1999) the validation of the weathering module of OSCAR with extended laboratory data is described.

We ran 9 ensembles of simulations, i.e. 3 drilling sites (A, B and C) X 3 simulation periods (1, 2 and 3), which are denoted as A1, A2, A3, B1, B2, B3, C1, C2 and C3, using wind and current data for each simulation period (obtained in Step 4), to determine the probability maps and the arrival times of the oil slick, and the probability for a percentage of oil mass to reach the shoreline of the Mesolongi – Aitoliko lagoons that is depicted in Table 1. The probability maps for the 9 ensembles of stochastic calculations are shown in Fig.2; the corresponding maps for the oil-slick arrival times can be found in the Supplementary Material (see Fig.S1). We refer to these ensembles as “stochastic” simulations, as opposed to “deterministic” simulations performed in step 8, where we model only a single oil spill. Each simulation was initiated every 3 hours and had a duration of 10 days; 401 simulations were performed for each ensemble resulting in a total number of 3609 simulations. For each of the 3609 simulations, we calculated the time-averaged thickness and the concentration of oil in the water column and ashore, as well as the minimum arrival time to shore. A 3-hour sampling interval was selected to provide reliable results for the specified release duration (Nordam et al., 2016), while the total simulation time was chosen equal to 10 days to allow oil spill tracking for a sufficient period, based on preliminary calculations that showed that a longer time did not affect noticeably the results.

Step 6. Determination of the worst-cases for each release site. Assuming that stranded oil is the most critical parameter that characterize a simulation and its threshold value is equal to 1 kg/km^2 (Bejarano and Michel, 2016; Nordam et al., 2016; Owens et al., 2008; Samaras et al., 2014), for each site, we calculated the stranded oil mass (t) for all the 1203 stochastic simulations and ranked them based on this value; then, we discarded from further analysis the simulations for which no oil ended up on shore, and finally we selected the 95th percentile (i.e. we eliminated 5% of the worst values) that are the “worst-cases”; these are: (A) For site A; winter season, time of blowout: 04:00 UTC (15/11/2015), (B) For site B; spring season, time of blowout: 02:00 UTC (29/03/2015), and (C) For site C; winter season, time of blowout: 13:00 UTC (20/11/2015).

Step 7. Determination of the main characteristics of the available oil spill response systems. Most oil spill response systems rely on mechanical recovery and/or dispersant application; in the present work, we consider both systems, for which we obtained the required data from the Environmental Marine Safety Agency (EMSA 2009, 2014a and 2014b). Currently, Greece possesses two main mechanical recovery vessels of a total capacity of 4000 m^3 of emulsified oil-water mixture that are located in Piraeus, whose mobilization time is estimated equal to 20 hours; also, there are 6 auxiliary vessels with capacities ranging from 6 to 27 m^3 and a total capacity of 90 m^3, whose mobilization times range from 8 to 24 hours. For dispersants application, there are 10 vessels available, but no aircrafts. Several stockpiles of dispersants are located all over Greece, including ports in the southern Ionian Sea; for these vessels, the time to start dispersant application is estimated to range from 3 to 24 hours. We applied the “newest oil" strategy, i.e. the vessels seek the oil that has been most recently released and we assumed that the volumetric dispersant: oil dosage ratio (DOR) is equal to 4%. In both systems, the turnaround trip time to the ports of Patras or Killini was estimated equal to 3-4 hours.

The EMSA evaluation of dispersants use in the European Union member states, which is endorsed by the Greek authorities (EMSA, 2014a), favors in confined marine environments and high sensitivity areas mechanical recovery with skimmers and booms over chemical removal. However, there are significant limitations of mechanical recovery, such as reduced effectiveness in rough seas, smaller covered area and limited availability. In the area of the lagoons, practically both methods cannot be applied due to the very small water depths (see Fig.1).

In OSCAR, oil is recovered mechanically at any time, when the oil is thicker than a prescribed limit that is equal to 0.1 mm and less viscous than the maximum oil emulsion viscosity (10^6 Cp); moreover, the following characteristics are also defined: operational speed=0.8 knots, skimmer rate=40.0 m^3/h and draught of the vessels that range from 2.0 to 6.4 m. The operation of the mechanical recovery is performed mainly via “switch off – switch on” controllers; thus, there is no oil removal when sea waves are higher than 2.0 m and when the local seawater depth is lower that the draught of the recovery vessels. Moreover, during night, the removal efficiency is reduced to 65% of its day value. Also, it is noted that OSCAR does not consider neither movable containment barriers (booms), whose movement is practically impossible to simulate by an OSM, nor steady booms near the coast due to the large opening (approximately 20 km) of the lagoons’ entrance. Dispersant application is modeled in OSCAR as a surface entrainment process, which in still conditions (no wind - zero wave height) is not activated; the main parameters that need to be set are: effectiveness of application, upper viscosity limit for the dispersant on the oil spilled, minimum thickness limit of the oil sprayed and the minimum dispersant-to-oil application ratio.

Step 8. Performance of deterministic calculations. We combined the 3 worst-cases A, B and C (see step 6) with the 3 response methods (see step 7) that are: no intervention (N), mechanical recovery (M) with skimmers, and surface dispersants (D), to formulate 9 scenarios that are denoted as follows: AN, AM, AD, BN, BM, BD, CN, CM and CD, for which we performed deterministic calculations with OSCAR. For each scenario, we calculated the path of the oil sick and the variation with time of the oil mass balance compartments (that are characterized mainly by the oil slick weathering processes), until it reaches its final state at the end of the computations (10 days). Indicatively, Fig.3 shows the path of the oil slick for scenario CN, i.e. for release site C and without any intervention; the corresponding paths of the rest 8 scenarios are shown in Fig.S2 to Fig.S9 of the supplementary material. Moreover, Fig.4 shows the variation with time of the oil mass balance compartments for the scenarios Cs, i.e. the worst-cases for the release site C; the corresponding figures for the rest scenarios for release sites A and B are shown in Fig.S10 and Fig.S11, respectively, of the Supplementary Material. In Table 2, the final state of the various compartments of the oil mass balance are shown.

Step 9. Assessment of the impact of oil spill in the areas of interest. To assess the impact of the oil spill on the Mesolongi – Aitoliko lagoons, we calculated the temporal variation of the percentage of the affected area and volume of the lagoons, which are plotted in Fig.5. As already mentioned in Step 4, the lagoon's area and volume are affected, when the surface oil thickness and dispersed oil concentration exceeded the threshold values of 0.01 mm and 10 ppm, respectively (see step 4). Moreover, since we assumed (see step 4) that Coot and Killfish are uniformly distributed in the surface area and the volume of the lagoons, respectively; then, the percentages of their affected populations can be approximated by the percentages of impacted area and volume, respectively, that are quoted in Table 3.

4. Discussion of the results

4.1. Stochastic calculations and oil spill pollution probability analysis

The probability maps that are shown in Fig.2 depend strongly on the season and the drilling site. In the spring period, for release sites A and B, the probability is higher in the northern and eastern part of the area of study, whereas for site C, it is higher inside the Gulf of Patras, to the east. In the winter period, the probability is high for site A at the island of Atokos and the east coast of Ithaki, for site B at the coasts of Zante and Kefalonia islands, and for site C at the western coast of Peloponnese and the northern coast of Zakynthos island. During summer, the west coast of Peloponnese to the south-east shows the highest values of probability for all three release sites. In all periods, for site C the probabilities are confined in a smaller area towards the north coastal areas of Peloponnese, thus reducing significantly the probabilities in the wider area. Fig.2 depicts that in the main areas of interest, i.e. the Mesolongi – Aitoliko lagoons, the highest values of pollution probability are observed for drilling site C; in the spring period, they range from 10% to 20% inside the lagoon and up to 30% in the west side and the entrance, while during winter and summer they range from 10% to 20% near the entrance and they are up to 10% inside the lagoon. For sites A and B, maximum probability reaches 10%.

From Table 1 that shows the probability for a percentage of oil mass to reach the shoreline of the Mesolongi – Aitoliko lagoons, it is depicted that the release site C shows the highest pollution probability; in spring, the maximum percentage of the oil mass for all 9 ensemble simulations that is equal to 67% is expected to reach the shoreline (13% of which with probability higher than 8%), while in summer and winter the corresponding values are 53% and 35%, respectively, with 8% and 10% having probability higher than 8%. For the sites A and B, the corresponding oil mass percentages are significantly lower. The release site A shows the lowest probability of oil spill pollution; only 12% of the oil mass for the worst period (spring) may reach the shoreline with very low probability (less than 2%).

4.2. Deterministic calculations - oil spill behavior and effectiveness of oil response systems

For the scenario CN, Fig.4 shows that the mass of oil at the surface increase with time from t=0 until t=5 d (end of release), when it reaches its maximum value (18645 t); then, it drops to 8882 t at t≈6.6 d and it reaches its final value (8328 t). At t=1.0 d, Fig.3 shows that the oil slick reaches the Mesolongi – Aitoliko lagoons (see also Table 2) and stranded oil starts to increase until it reaches its final value (4461 t); moreover, the rate of increase of stranded oil from t=1.0 to 1.6 d is relatively high (3273 t/d), at the expense of the rate of increase of the surface oil that is reduced to 1317 t/d, from 5613 t/d at the period t=0.0-1.0 d. The amount of oil that evaporates, shows a linear increase during the period of release (t=0.0=5.0 d) with almost constant rate (2890 t/d), while its final value is equal to 16033 t. At t=3.7 d, Fig.3 shows that oil reaches the north boundary of the computational domain and starts to exit; at the end of calculations (t=10 d) the mass of the “outside” oil reaches its final value that is equal to 7057 t. The formation of oil droplets (“droplet oil’) is generally small with small rates, except for a short period (t=4.9-5.1 d), when very high wind velocities occurred; its final value is equal to 90 t. The final amount of oil that settles (“sedimented” oil) is 5204 t. The amounts of oil that dissolves (dissolved oil) and biodegrades (biodegraded oil) are relatively small; their final values are equal to 42 t and 1021 t, respectively, and do not affect significantly the oil mass balance. At t=10 d, Fig. 4 shows that there exists a significant amount of oil with high thickness in the area of study that remain mainly the lagoons.

The calculations for scenario CM show that mechanical cleaning does not affect noticeably the path of the oil slick (see Fig.S2) and the temporal variation of oil mass balance (see Fig.4). The effect of mechanical recovery that starts at t=8 hours (see step 7), is the “presence” of cleaned oil, which appears at t=0.33 d and increases continuously with time, initially (t=0.33-5 d), with a high rate (688 t/d) and then with a very slow rate 85 t/d, due to limitations of the mechanical cleaning, until it reaches its final value (3635 t) that accounts for 8.6 % of the released oil quantity. Cleaned oil is “taken” from the surface oil, whose final amount is reduced by 11 % (see Table 2). Subsequently, the other forms of transformed oil (evaporated, dissolved, sedimented and biodegraded) are also reduced by 6-9%, except for the “droplet” oil that increases by 21%; in any case, the amounts of dissolved and biodegraded oil remain very low. The use of dispersants (see for example Fig.S3 for scenario CD) does not affect significantly the path of the oil slick, but it has an impact on the temporal and final oil mass balance (see Fig.4 and Table 2); the final amount of the surface oil decrease drastically (72 %) and subsequently the evaporated oil is reduced. The “removed” surface oil is transformed into oil droplets (from 90 t without dispersants to 8862 t) and then to dissolved, sedimented and biodegraded oil, whose increase are also very pronounced and equal to 342, 76 and

224 %, respectively. It is interesting to note, that the mechanical cleaning and the use of dispersants result in the decrease of the amount of oil leaving the computational domain, due mainly to the decrease of surface oil; when dispersants are used; this “outside” oil is further reduced by the large amounts of droplet oil that are present in the water column and move with lower flow velocities. Finally, Table 2 depicts that the final amount of stranded oil is practically not affected by the mechanical recovery (its reduction is only 2%), while the use the dispersants seems to have a more pronounced effect, since the reduction is 16%.

The paths of the oil slicks depend strongly on the characteristics of the worst-case scenario, which are mainly the release site and the temporal-seasonal variation of wind velocities, and are very different between each other (see Fig.3 and Fig.S2 to Fig.S9). However, as shown in Table 2, the corresponding differences in most of the oil mass balance compartments are not very significant. For example, the reductions of the amount of surface oil are equal to 14 %, 13 % and 11 % for scenarios AM, BM and CM, respectively, and equal to 74 %, 70 % and 72 % for scenarios AD, BD and CD, respectively, while the corresponding decreases of the evaporated oil are equal to 7 %, 7 % and 6 % for scenarios AM, BM and CM, respectively, and equal to 19 %, 20 % and 28 % for scenarios AD, BD and CD, respectively. Also, the differences of the quantities of the stranded oil are relatively low; they range from 0 % to 5 % with mechanical cleaning and from 16 % to 21 % with dispersants. These higher values of stranded oil with dispersants result in the decrease of the quantities of “outside” oil that range from 56 % to 78 %, which are significantly higher than the corresponding range of values with mechanical cleaning (11-22%). The “cleaned” oil with mechanical recovery for scenarios AM and BM are equal to 10.1 % and 9.9 % of the released quantity of oil, respectively; these values are somehow higher than the value for scenario CM (8.6 %). It is worth noting, that the mass of droplet oil is generally high for scenarios As, i.e. AN, AM and AD, due to the very high wind velocities (7-15 m/s) in the period t=6.4-7.2 d (see also Fig.S10) that result in high current velocities, which favor the formation of droplet oil.

4.3. Impact of the oil spill on the Mesolongi - Aitoliko lagoons

Fig.5 shows that the oil slick arrives at the lagoons at t=1.0 d, 5.0 d and 6.4 d, for scenarios As, Bs and Cs, respectively; the arrival time of the oil slick does not depend on the oil response system (see also Fig.3 and Fig.S2 to Fig.S9). It is noted, that once the oil slick enters the lagoons, no mechanical recovery is performed due to very shallow water depths, while the almost still waters in the lagoon that do not favor natural dispersion of oil by wave action, practically eliminate the effectiveness of dispersants’ applications.

Fig.5 depicts that the effect of mechanical recovery on the affected area is practically negligible; the variation of the affected area with time for scenario BN coincides with BM’s, for CN coincides with CM’s, while the transient values of the affected area for scenario AM are somehow lower than for scenario AN (due to the longer arrival time to the lagoons for scenarios A’s); correspondingly, the final values of the affected area (see Table 3) are equal to 90.0 % and 85.4 % for scenarios AN and AM, respectively, 87.5 % for both scenarios BN and BM and 78.0 % for both scenarios CN and CM.

When we use surface dispersants, i.e. for scenarios AD, BD and CD, Fig.5 shows that the variation lines of the affected area follow similar patterns with or without mechanical recovery; however, with much lower values of affected area (see Table 3), whose final values are equal to 70.0 %, 77.1 % and 69.3 %, for scenarios AD, BD and CD, respectively. In other words, the use of dispersants is more effective to reduce the impacted by the oil spill area of the Mesolongi – Aitoliko lagoons. It is interesting to note that although for scenarios Cs the distances of the release site C from the lagoons and the arrival times (1.0 d) are shorter than Bs and Cs, in the long run scenarios Bs and As affect a larger percentage of the area of the lagoons. Fig. 5 depicts that the effect of mechanical recovery on the affected volume is also not important; similarly, the final values of affected volume (see Table 3) are equal to 4.9 % and 4.2 % for scenarios AN and AM, respectively, 2.0 % for both scenarios BN and BM and 1.7 % for both scenarios CN and CM. The effect of the dispersants on the impacted volume is negative, since the final values are equal to 6.0 %, 8.0 % and 8.5 %, for scenarios AD, BD and CD, respectively; this is because the dispersed oil stays remains in the water column the form of droplets in large quantities.

To summarize, a large part of the lagoons' surface is expected to be contaminated in the case of an oil spill. Mechanical recovery did not affect noticeably the oil slick. The use of dispersants is probably the most efficient response method, because it achieves a noteworthy reduction of the affected area and thus of the affected birds (Coot) population, while the corresponding increase of the affected volume and thus affected fish (Killifish) population is significantly lower. This rather straightforward conclusion, which is based on a series of assumptions that were made throughout the application of the proposed methodology including the simplified approach regarding the characteristic of the sensitive species (see Step 2), needs to be verified or not at the final design stage, when more information and data are expected to be available; see section 5.

5. Conclusions and suggestions for future research

We developed and applied a modeling procedure that employs stochastic and deterministic oil spill simulations in the Gulf of Patras. We have performed calculations for three typical seasonal weather variations of the year 2015, three oil release sites and specific oil characteristics, and derived the following conclusions:

1. Stochastic calculations showed that there is a considerable probability of oil pollution in the Gulf of Patras that may reach 30% in the Mesolongi – Aitoliko lagoons.

2. Deterministic calculations showed that 78-90 % of the bird population and 2-4 % of the fish population are expected to be contaminated in the case of an oil spill without any intervention. For the current oil response systems in Greece, the use of dispersants reduced the amount of stranded oil by approximately 16-21 % and the contaminated bird population of the lagoons to approximately 70 %; however, the affected fish population increased to 6-8.5 % due to the higher oil concentration in the water column. Mechanical recovery with skimmers "cleaned" almost 10 % of the released oil

quantity, but it did not have any noticeable effect on the stranded oil and the affected bird and fish populations.

The present work is a first attempt towards the formulation of a detailed management plan for the abatement of oil spill contamination in the Gulf of Patras caused by an accidental subsea blowout; the results of the present simulations may be used at a preliminary stage of design (a) to choose the most appropriate drilling site from the possible alternatives that will be determined based on the current seismic surveys, and (b) to select the most effective oil spill response method. Subsequently, any generalization of the results over space and time should be considered with caution. Moreover, to improve the statistical result of the computations (Nordam et al., 2016) at the final stage of design, we suggest applying the present methodology to perform "updated" calculations using a larger number of time-periods and a wider range of blowout characteristics. In these calculations, we need to take into account the "updated" response tools, since we expect that the development of the first exploitation sites of marine petroleum in the western seas of Greece will be accompanied by the supply of adequate response tools (vessels and equipment to support the existing ones) that will be located close to the drilling sites, which will allow a faster intervention to slow down the expansion of the oil slick.

6. Acknowledgements

The authors would like to thank Prof. G. Kallos for providing the data from SKIRON.

Funding: Part of the present work was realized via the program "Scholarships of IKY in the Marine and Inland Management of Water Resources" and was co-funded by EEA grants - Financial Mechanism 2009-2014 (85%) and the General Secretariat for Investments and Development (15%).

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Artwork

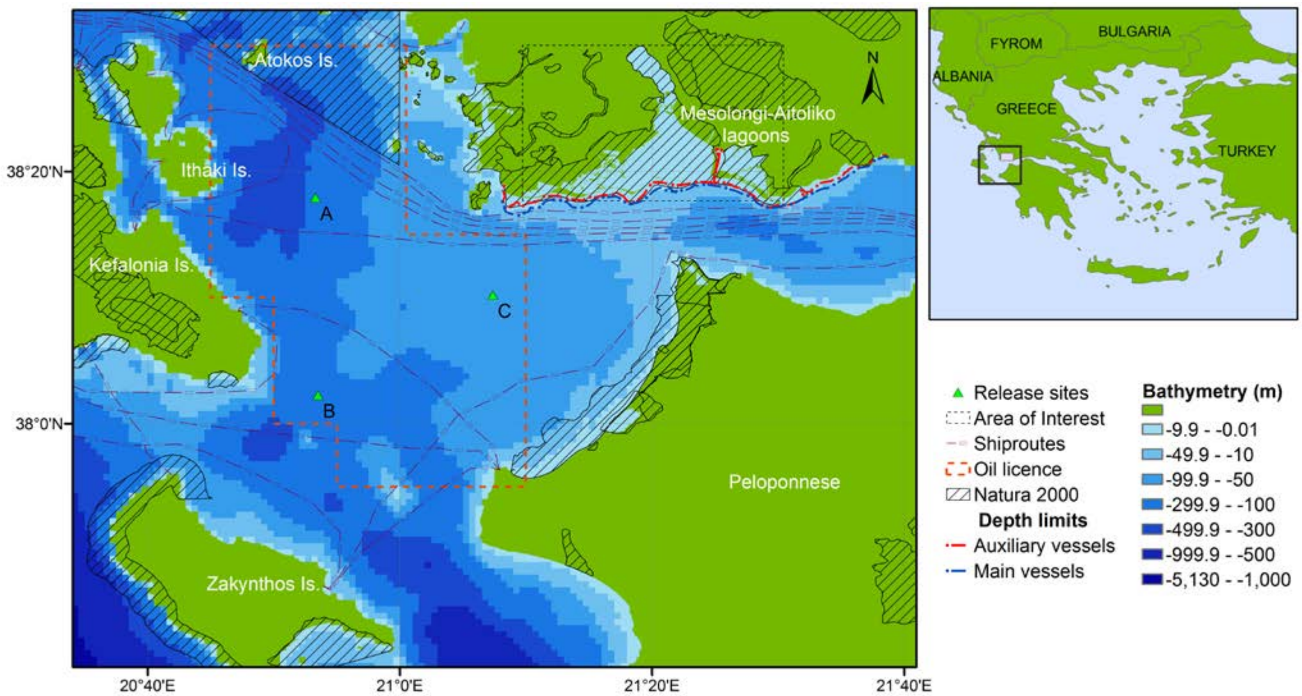

Fig.1. Area of study.

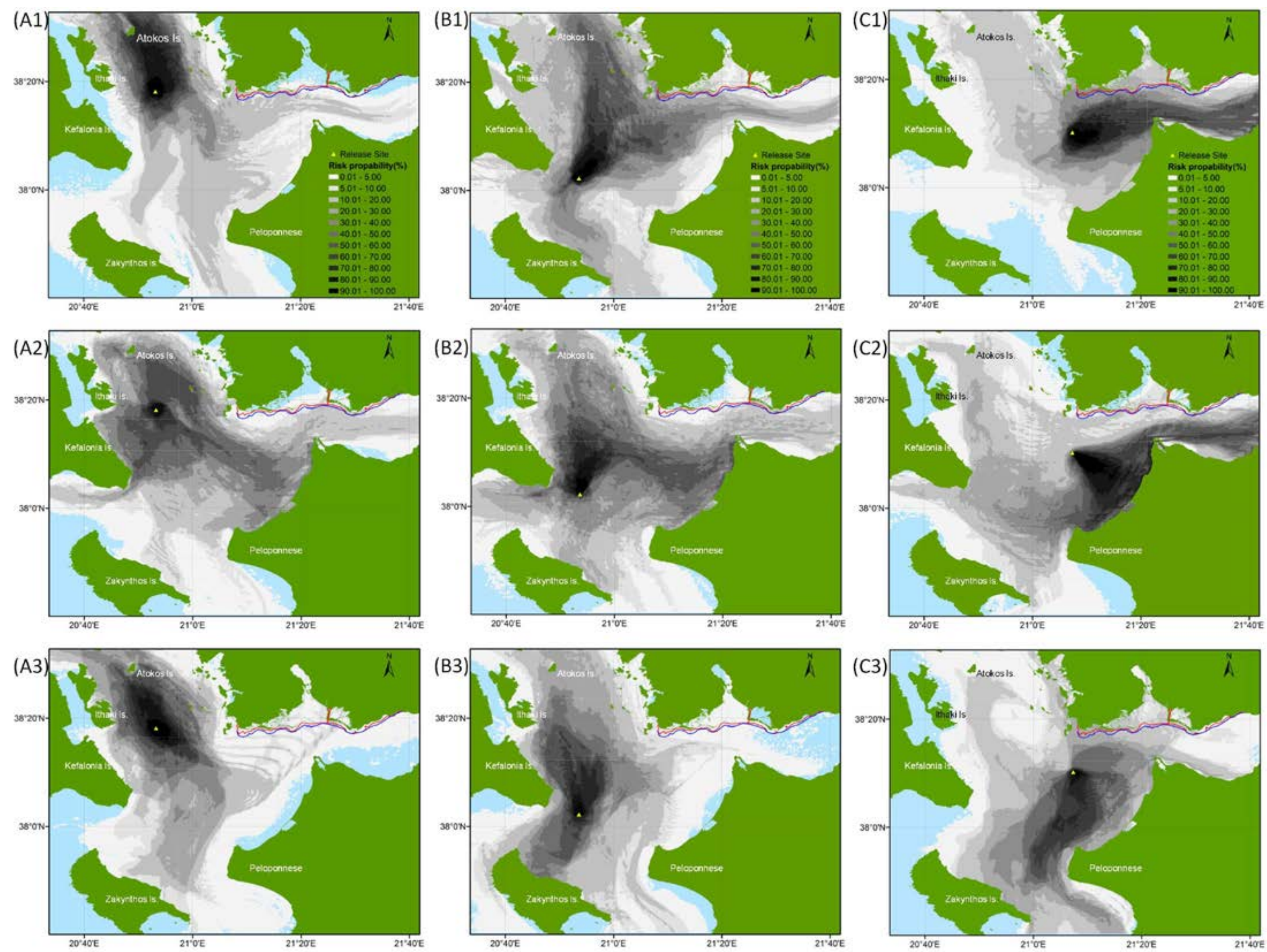

Fig.2. Probability risk maps for the 9 ensembles of stochastic calculations; the probability risk in a grid cell is calculated as the number of simulations, for which oil reached this cell, divided by the total number of simulations.

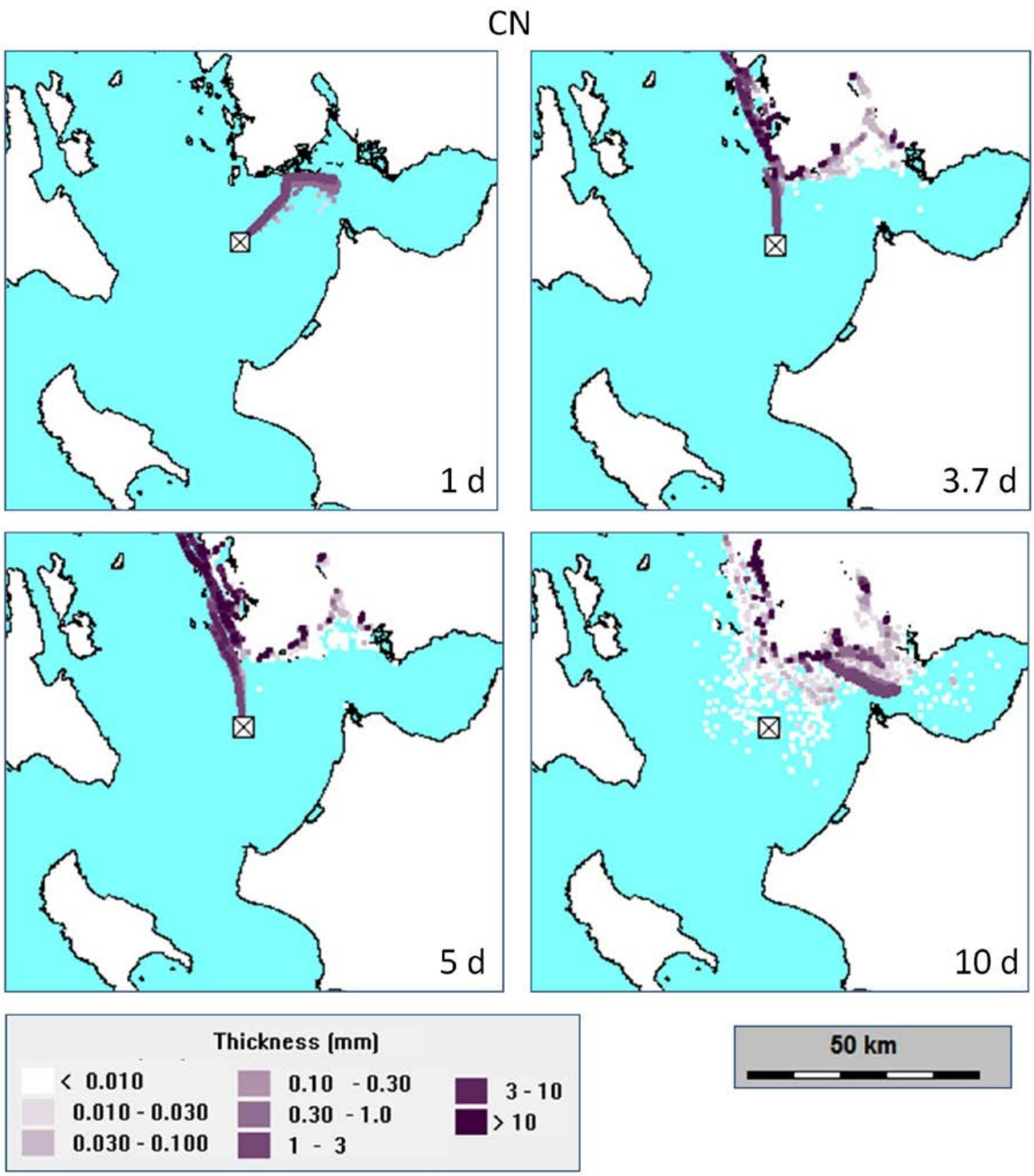

Fig.3. Path of the oil slick for scenario CN at times t=1 d, 3.7 d, 5.0 d and 10.0 d.

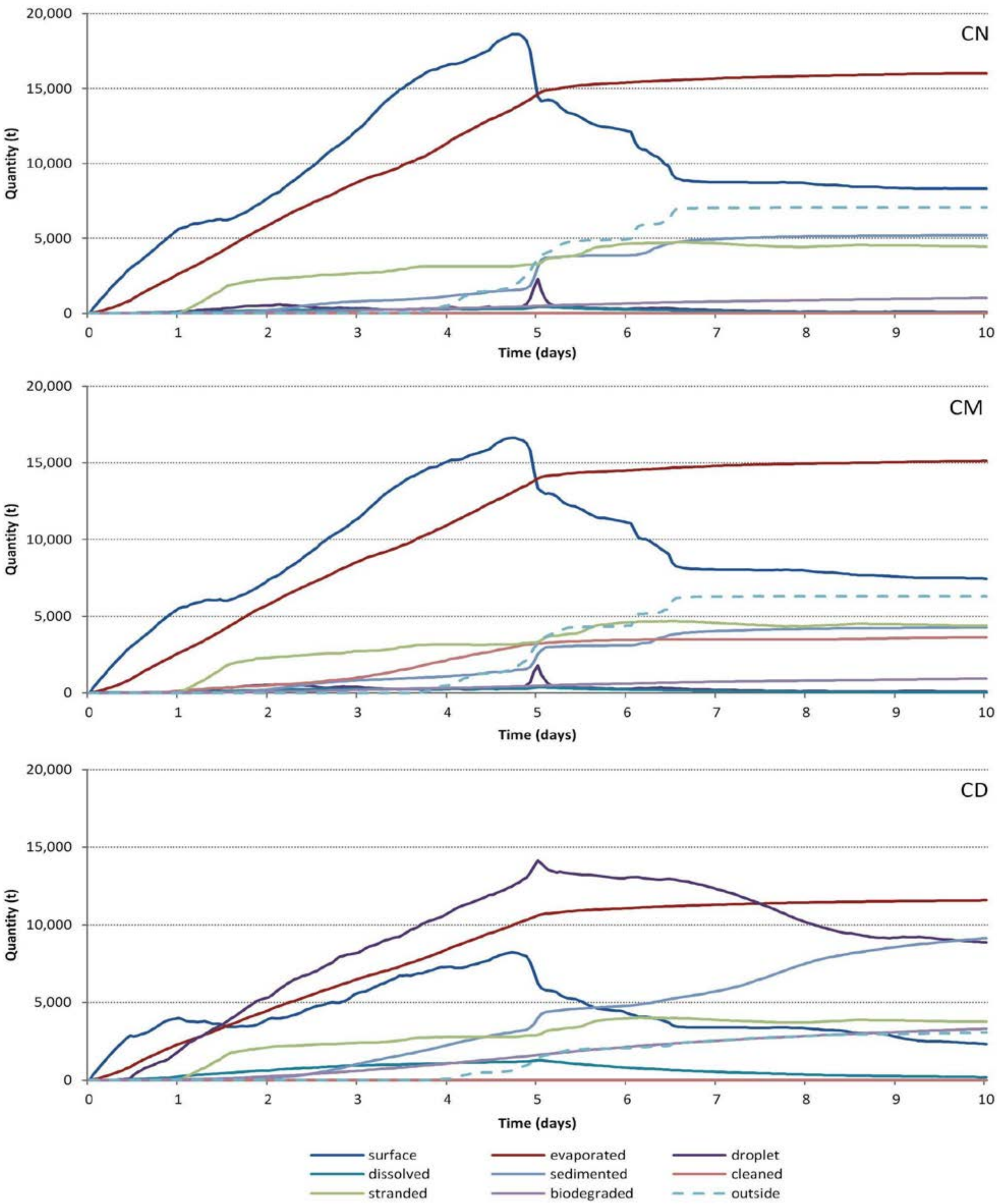

Fig.4. Temporal variation of oil mass balance compartments for scenarios CN, CM and CD.

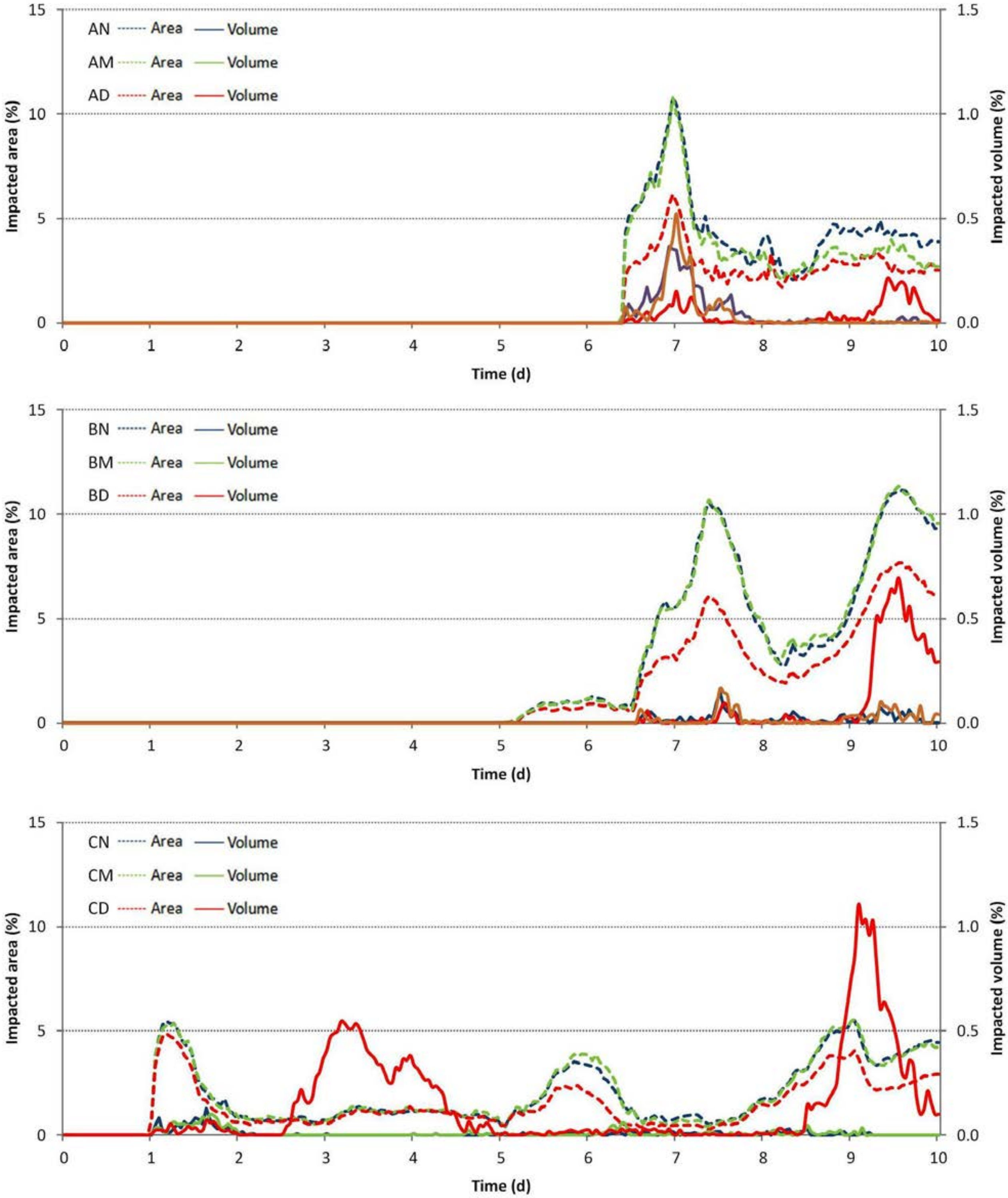

Fig.5. Temporal variation of the affected area and volume of the Mesolongi – Aitoliko lagoons.

Tables

Table 1. Probability for a percentage of released oil mass to reach the shoreline of the Mesolongi – Aitoliko lagoons.

Site	Ensemble Simulation	Percentage of oil mass (%) / Season	>10	8-10	6-8	4-6	2-4	<2	0
A	A1	Spring	0	8	2	1	1	2	86
	A2	Summer	0	0	0	0	0	31	69
	A3	Winter	0	0	0	0	0	24	76
B	B1	Spring	0	2	6	2	2	54	34
	B2	Summer	0	0	0	0	0	41	59
	B3	Winter	0	0	0	0	10	14	76
C	C1	Spring	0	13	2	5	3	44	33
	C2	Summer	3	5	1	1	1	42	47
	C3	Winter	5	5	5	7	1	12	65

Table 2. Final oil mass balance compartments (t).

	AN	AM	AD	BN	BM	BD	CN	CM	CD
Surface	8959	7717	2342	10631	9246	3205	8328	7453	2314
Evaporated	17344	16213	13994	18012	16796	14444	16033	15125	11587
Droplet	697	714	11812	256	287	9624	90	109	8862
Dissolved	63	57	98	22	21	40	42	39	184
Sedimented	2302	2331	5121	851	718	7093	5204	4262	9144
Cleaned	0	4265	0	0	4185	0	0	3635	0
Stranded	4525	4314	3555	4621	4632	3918	4461	4379	3759
Biodegraded	831	768	2072	669	650	2330	1021	929	3309
Outside	7515	5857	3240	7174	5700	1582	7057	6304	3076

Table 3. Percentages of total impacted area and volume of the Mesolongi – Aitoliko lagoons.

Site	Oil response system	Scenario	Affected area or Affected Coot population (%)	Affected volume or Affected Killifish population (%)	Oil arrival time (d)
A	None	AN	90.0	4.9	6.4
	Mechanical	AM	85.4	4.2	6.4
	Dispersant	AD	70.0	6.0	6.4
B	None	BN	87.5	2.0	5.0
	Mechanical	BM	87.5	2.0	5.0
	Dispersant	BD	77.1	8.0	5.0
C	None	CN	78.0	1.7	1.0
	Mechanical	CM	78.0	1.7	1.0
	Dispersant	CD	69.3	8.5	1.0