Research Article

Oil spill vulnerable areas in Arzew Gulf: a study case

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Abstract

This study focuses on the Gulf of Arzew in Oran, an important area of the Algerian economy and the first Algerian port in terms of hydrocarbon exports. Oil spills in this area represent a severe risk that can disrupt the marine and coastal ecosystem. Therefore, the aim is to estimate marine waters' vulnerability to oil pollution, which has become a significant problem worldwide. Predictive simulations of oil slick drift, which may occur in the coastal area of Arzew in Oran, northwest Algeria, were carried out to study, prevent and map the spread of an oil spill in the context of a hypothetical oil spill. For this purpose, the National Oceanic and Atmospheric Administration's general operational oil modeling environment and the Automated Data Inquiry for Oil Spills were also used. The results show that approximately 29.7 km of shoreline could potentially be impacted by oil during the winter season, with an evaporation rate of more than 74.6% of the spilled amount. In addition, the simulation results indicate that the area could be affected in distinct ways depending on the season, with completely different oil slick trajectories. It is important to note that no oil slick modeling work has been done in this area to date, although oil spills represent a serious risk that can disrupt coastal resources such as fisheries, tourism, aquatic life, and shoreline physical resources. The mapping results propose a new transposable approach to coastal risk and could serve as a decision-making tool.

Article highlights

- The study of coastal vulnerability to oil spills in the Gulf of Arzew reported that Cap Carbon, Arzew, and Pont aux Poules have extremely high sensitivity.
- The heavier oil components of ALGERIAN BLEND and ALGERIAN CONDENSATE STATOIL remain in the sea, causing serious physical and chemical effects on the marine environment.
- According to simulation results, some spilled oil washed up on the Gulf of Arzew, while others remained at sea after 48 h.

Abbreviations
ADIOS   Automated Data Inquiry for Oil Spills
PCA   Port Company of Arzew
GNOME   General National Oceanic Modeling Envirot
LNG   Liquefied Naturel Gas
LPG   Liquefied Petroleum Gas

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NCC   National Climatological Center
NOAA   National Oceanic and Atmospheric
         Administration

1 Introduction

Oil pollution, mainly caused by tanker accidents, is a primary concern for marine environmental protection [50]. Oil spills are one of the most significant risks to coastal waters [45]. They will be subjected to various physical, chemical, and biological oil weathering processes that alter their chemical composition, physical properties, and environmental fate [15]. These are the processes of evaporation, emulsification, natural dispersion, dissolution, photooxidation, spreading, sedimentation, interaction with fine particles, and biodegradation [55]. The relative rates of these processes determine the degradation levels of marine waters. The fact that the oil remains at sea or comes ashore also influences its fate.

Algeria is geographically, economically, politically, and strategically located on one of the Mediterranean Sea's main coastlines. Indeed, it is strategically located in the Western Mediterranean. It is the largest country in the Mediterranean, with a surface area of 2.4 million km^2, or about 4.5 times the size of France and 8 times the size of Italy, and a maritime facade of about 1200 km, facing Europe, its main economic partner, particularly for exporting most of its oil and gas and importing most of its capital and consumer goods. The Mediterranean coasts are home to more than twenty states and over 400 million people, of which about 130 million, or 35%, live in the coastal zone [5–24, 59]. The coast hosted about 300 million tourists in 2014, or 30% of global tourism flows; about 50% of these visits took place on the coast [58]. The coastal zone is a very sensitive environmental area [24] and is the seat of many maritime activities, mainly the maritime transport of hydrocarbon [25], anarchic urbanization, and intense port activities associated with various industrial activities[52]. Pollution accidents can have catastrophic impacts on the marine environment in the long term.

Crude oil is essential for global development [8, 14, 27, 33, 35, 51]. Over time, the increase in world population [21, 53] multiplied the oil production rate to about 9947 billion ton-miles [23]. Oil production in Algeria reached about 48.3 million tons in 2018. The number of exploration drillings in 2019 reached 80 wells [11]. Algeria occupies the 3rd rank among the oil-producing countries in Africa and the 12th rank globally. A significant portion of it is transported by sea yearly [27]. Two billion tons of goods are circulating in the Mediterranean [4, 5], including 370 million tons of hydrocarbons transiting annually. Twenty-six (26) million tons of general cargo are destined for Algerian ports, from which one hundred (100) million tons of hydrocarbons are loaded for export. The latter, being the economic and political will of the State, aims to create a large industrial zone near Oran, which has transformed the city, and the port of Arzew, a small fishing port, has become, in a few years, a large hydrocarbon port [3]. The latter is still the largest and the main source of the national economy, where the choice of application lies. Maritime transport is a market worth nearly €1.5 trillion representing 80% of the world's commercial traffic [19, 42].

Several works have been done in this context [38, 51]. Different mathematical models of oil slick drift have been developed to simulate their trajectories, and these models have been applied in different studies worldwide [8], including OSCAR, webGNOME, Medslik-II and SIMAP [8, 20–22]. The most comprehensive and successful models used in the trajectory and fate of oil spills due to their high predictive accuracies are General NOAA Operational Modeling Environment (webGNOME), Automated Data Inquiry for Oil Spills (ADIOS) and Oil Modeling Application Package (OILMAP) [9, 13, 34, 35, 43, 51, 58]. Compared to other models, the webGNOME model can be used worldwide, requiring fewer input parameters [12]. What, we used webGNOME for this study. webGNOME has been validated based on observations of many oil spills worldwide [2, 18, 28].

Section 1 presents a brief introduction, and Sect. 2, materials and methods, which includes 4 subsections including the study area, the modeling systems used, the entrance data and boundary conditions, and the modeling scenarios; this subsection presents the results found during the different tests of the different possible scenarios in the Gulf of Arzew. Section 3 presents the results and discussion, and Sect. 4 the conclusion and recommendations.

It is important to estimate the vulnerability of marine waters to oil pollution, which has become a significant problem worldwide. Solutions are needed to contain this pollution and avoid future damage to the marine and coastal environment [41]. To this end, the main objective of this study aims to use predictive simulations of the oil slick drifts, which can occur at the level of the coastal zone of Arzew in Oran, northwestern Algeria.

2 Materials and methods

2.1 Study area

The study area is located in the northwestern region of Algeria. The Gulf of Arzew is located about 350 km West of Algiers and 40 km East of Oran in a semi-arid region. Its climate is characterized by a moderate winter and a dry and humid summer. Algeria is geographically, economically,

politically, and strategically located on one of the Mediterranean Sea's main coastlines. Indeed, it is strategically located in the Western Mediterranean. It is the largest country in the Mediterranean, with a surface area of 2.4 million km^2, or about 4.5 times the size of France and 8 times the size of Italy, and has a maritime facade of about 1200 km, facing Europe (Fig. 1) its main economic partner, in particular for exporting most of its oil and gas and importing most of its capital)and consumer goods [31, 32, 62]. The wilaya of Oran contains eight important natural wetlands that, by geographical location, strategic, ecological, hydrological functions, biodiversity, and socio-economic importance, represent the best examples of wetland ecosystems in Algeria [6, 30]. Only four sites are currently on the Ramsar list of worldwide importance: Telamine Lake, the Arzew salt flats, the Great Sebkha in the wilaya of Oran, and the Macta marshes in the wilayas of Oran, Mascara, and Mostaganem [32].

According to December 2019 figures, the total population of the wilaya of Oran was approximately 2,118,603 people, with a population density of 1152 persons/km^2.

This density varies from commune to commune. Indeed, the presence of the most productive agricultural area, transportation and communication infrastructure, and all the amenities required for industrial activity only intensifies the human concentration on the coastal strip. Socioeconomic developments and economic practices further strain the coastline [62]. The shoreline's degradation results from population pressures and activities affecting the metropolitan areas of Algiers, Oran, Annaba, and Skikda. During the first economic census in 2011, 934 250 economic enterprises were counted on the national territory. More than 46% of these entities are found along the coast, with a significant concentration in the wilayas of Algiers and Oran, which account for 10.38% and 5.66% of all economic entities, respectively. 60% of the 934,250 economic enterprises surveyed (construction, trade, industry, and services) are in coastal wilayas [62].

Table 1 summarizes the characteristics of Bethioua and Arzew and shows that the two ports remain the most important regarding hydrocarbons' reception and loading capacity. The types of vessels regularly calling at Arzew/
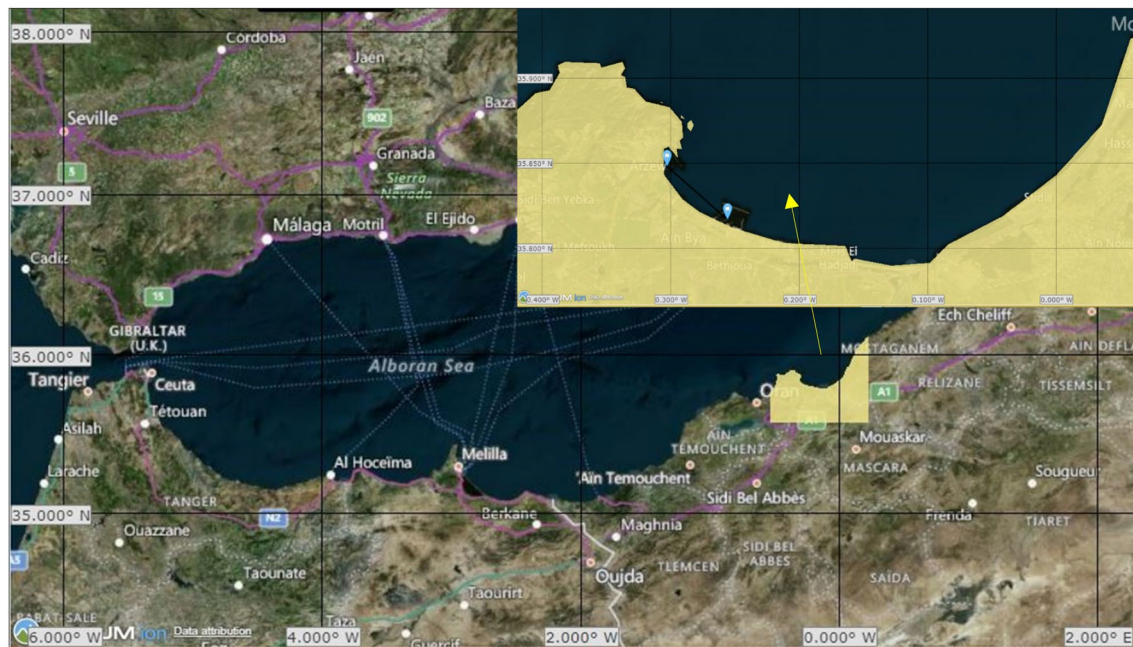

Fig. 1 The geographic location of the study area and the two ports, Arzew and Bethioua (webGNOME)

Table 1 Characteristics of the two ports, Arzew and Bethioua [36]

Port	Number of docks	Dock capacity/receiving volume (m^3)	Number of loading arms	Loading flow rate (m^3/h)	Draft of water (m)
Bethioua	4	2 Receptions for 40,000 to 125,000 and 2 for 50,000 to 125,000	5	4103 to 10,103	13.5
Arzew	1	25,000 to 50,000	4	Max 103	9.8

Bethioua are Crude Oil Tanker (24%), LPG Tanker (21%), Bulk Carrier (15%), General Cargo (13%), Oil/Chemical Tanker (7%). The maximum length of the vessels recorded to have entered this port is 298 m. The maximum draught is 15 m. The maximum Deadweight is 174008 t.

2.1.1 Transport of hydrocarbons in the Gulf of Arzew

Maritime traffic is very dense (nearly 40% of the world's commercial maritime traffic passes through our coasts) in addition to 100 million tons of oil exported annually by Algeria, which also receives refined products through its terminals in Algiers and Arzew (Table 2) [65]. The port of Arzew is the first Algerian port for hydrocarbon exploration. Its main role is to load the different ships (oil tankers, LNG ships, LPG ships, chemical tankers) from different

world regions with crude oil and refined products. These activities generate serious environmental pollution risks [65]. Table 2 lists the main indicators of the port activity in Arzew and Bethioua.

Major accidents have occurred in the port of Bethioua with the following outstanding facts: devastating and heavy consequences on the human, environmental and material plateau, recurrence in their occurrences. Hence, studying them to avoid them in the future is essential. Statistics concerning the transport of hydrocarbons by the sea in the Gulf of Arzew (Fig. 2) highlight our choice of study area. There is always a relationship between the density of maritime traffic and the risks of accidents and pollution, affecting the quality of seawater, marine biodiversity, and coastal resources. Maritime security encompasses the safety of human life and protecting property at sea from environmental and operational threats [44].

It is important to estimate the vulnerability of marine waters to oil pollution, which has become a significant problem worldwide. Solutions are needed to contain this pollution and avoid future damage to the marine and coastal environment [41]. To this end, the main objective of this study aims to use predictive simulations of the oil slick drifts, which can occur at the level of the coastal zone of Arzew in Oran, northwestern Algeria. webGNOME software and the oil slick weathering model ADIOS- NOAA were used to measure how the oil spill threatens the environment [46], to predict which areas will be affected and which areas are most at risk, and to see how the oil spill is expected to change chemically and physically over time [57]. In this study, scenarios for each season (winter, autumn, summer, and spring) were carried out to encompass all the possible seasonal scenarios. It is important to note that this is the first study performed in this area in

Table 2 Main indicators of port activity per year [32]

	2017	2018
A—Production indicators		
1—Global traffic (tons)	22,198,600	22,163,615
1.1 Import traffic	1,447,355	1,280,630
1.2 Export traffic	20,751,245	20,882,985
2—Miscellaneous goods (tons)	291,093	257,302
2.1 Import	220,514	172,509
2.2 Export	70,579	84,793
2.3 Hydrocarbon traffic (ton)	21,273,978	20,143 507
2.3.1 Import	1,162,142	78,434
2.3.2 Export	20,111,836	19,065,073
B—Movement and navigation indicators		
1-Number of vessels at the entrance	679	688
1-Number of ships at the exit	678	692
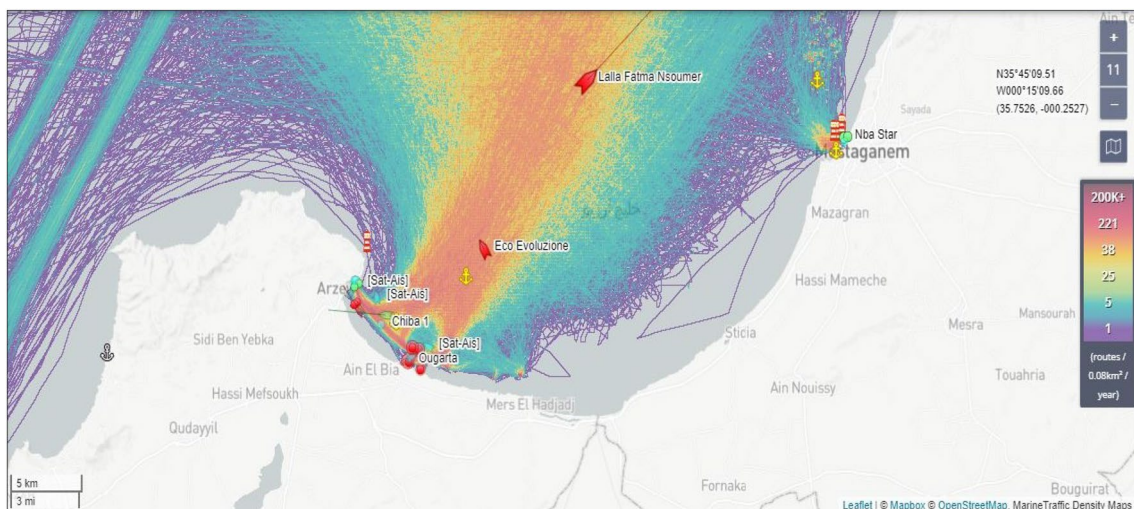
Fig. 2 Map of maritime traffic in the Gulf of Arzew, Source: https://www.marinetraffic.com

the golf of Arzew to date and can serve as a reference for future studies.

2.1.2 Sensitivity maps

Shoreline mapping gives critical information on the sorts of shorelines (sandy, muddy, rocky) and the species present there to identify biologically susceptible to oil spills and culturally important locations along the coastline.

Recent maps of coastal vulnerability to pollution were developed (Figs. 3, 4, 5, 6), which include physical shoreline types (Fig. 3), biological, ecological (Fig. 5), and socioeconomic (Fig. 4) features susceptible to oil spills. The map's realization and classification are based on a list of existing literature [7, 8, 26], site visits, and the location of various coastal resources using ArcGIS software, an integral component of the oil spill decision support system [1, 18, 56, 61]. This allows the emergency response team

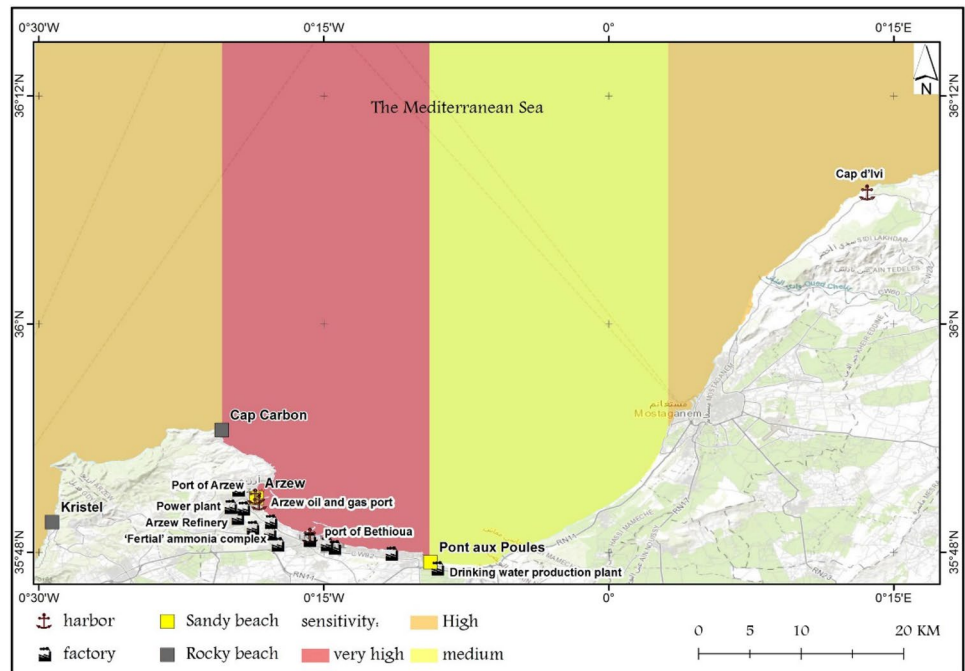**Fig. 3** Physical sensitivity map of the coastal area of Arzew (ArcGIS, 2022)

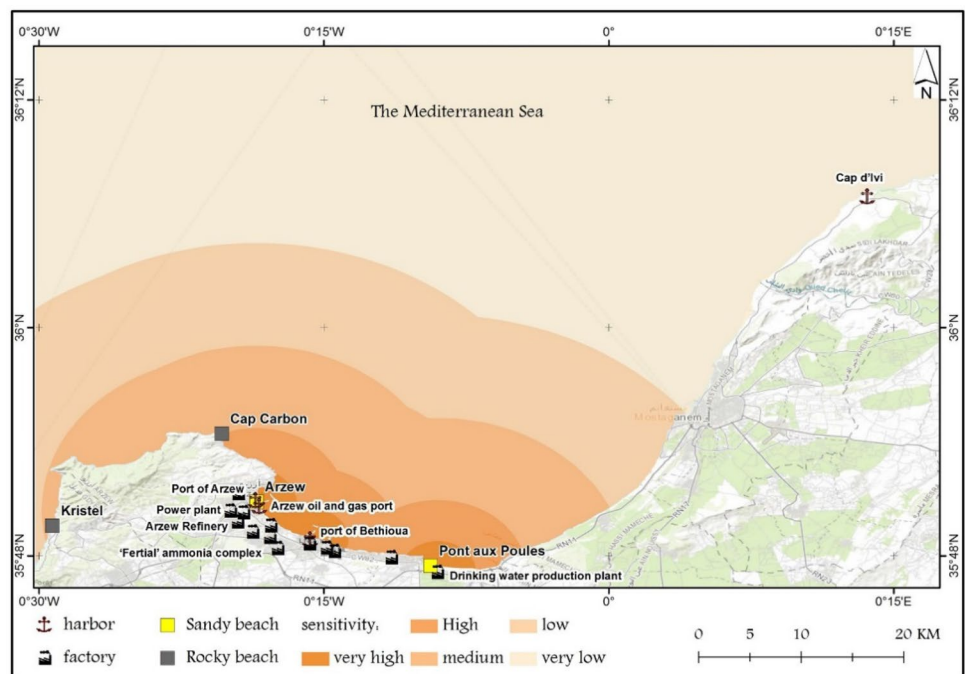**Fig. 4** Socio-economic sensitivity map of the coastal area of Arzew (ArcGIS, 2022)

Fig. 5 Ecological and biological sensitivity map of the coastal area of Arzew (ArcGIS, 2022)
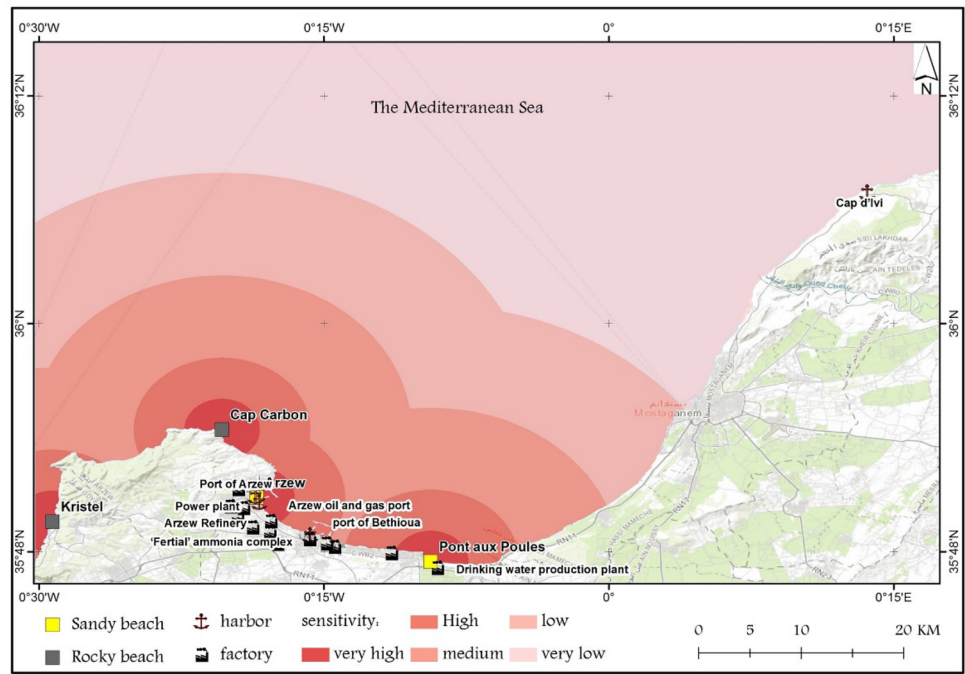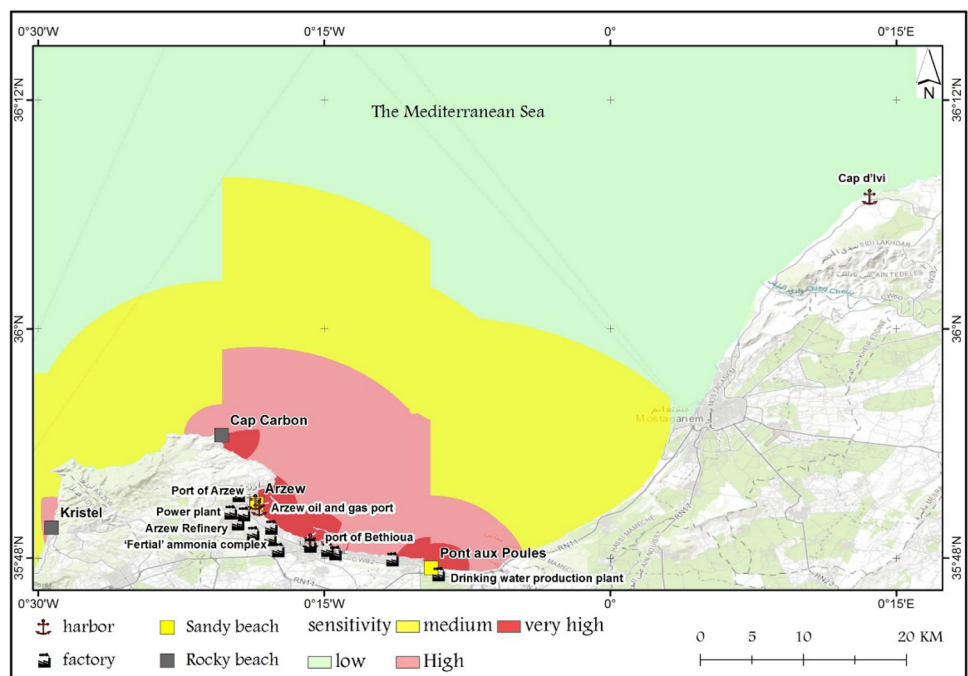

Fig. 6 Coastal oil spill vulnerability map (ArcGIS, 2022)

and decision-makers to holistically identify areas vulnerable to oil spills.

Figure 3 indicates the physical sensitivity based on the characteristics of the shoreline, soft sandy substrate or rocky substrate, beaches, and seabed that contribute to biological activity and are resistant to impacts associated with oil spills. The study area was divided into 4 zones according to the degree of physical sensitivity.

The classification of the analyzed sites depends strongly on the degree of anthropic occupation, as observed by Rangel-Buitrago et al. [51].

Figure 4. shows that socio-economic sensitivity is based on the human use of resources that contribute to the economy of the area tourism, port, and factories). As for Fig. 5, the evaluation of the different study sites in terms of habitats and ichthyic populations indicates:

- Very high-value area (evaluation ≥ 20): Eastern sector (Cap Carbon and Arzew)
- High value area (rating ≥ 10): Central area (Pont aux Poles) + Eastern area of Kristel
- Medium value area (evaluation < 10): West of Kristel + East Cap d'Ivi towards Mostaganem

These areas have significant ecological and conservation value (including their species and habitats.

The map in Fig. 6 represents the balance of the 3 coastal sensitivity maps (physical, socio-economic, and biological). It allows the classification of certain areas resistant to protection and essential areas such as the Kristel Cap Carbon area of implementation of artificial reefs, Pont aux poules, and the wetland of Mecta, which has importance established under the Ramsar Convention 2001. These areas are environmentally important and can be affected by oil slicks.

Prior data gathering is used to identify the right cleanup technique(s) to respond to an oil spill (on water or shoreline). It entails locating and mapping sensitive sites, habitats, and wildlife populations so that response teams can access professional, scientific assistance during an incident. In the case of a spill, this information and the vulnerability maps are made available to response teams for effective decision-making and speedy deployment.

2.2 Modeling system

In the event of an oil spill in the aquatic environment, knowledge of the oil slicks' trajectory is essential to organize the recovery of the oil and protect the areas exposed to the risk of pollution [40]. The development of oil slick drift models in continental waters and at sea is motivated by the frequency of pollution and the harmful impact on the environment. Numerical models make it possible to study the impact of various possible scenarios and thus estimate the environmental sensitivity of a coastal maritime area even before such accidents occur [8].

The ability to rapidly predict oil spill trajectories in real-time on a global scale [31] was achieved through the integration of oil spill modeling tools with hydrodynamic and meteorological data sets [22] obtained from Arzew weather stations based on MODIS satellite images (2013 to 2022) [10] and also from in situ measurements made during sea trips (2013 and 2018). Access to data allows for timely probabilistic analysis of spills. For all other spill information, the ADIOS model [37] was used; this is the NOAA oil weathering model. It quickly estimates and models spilled oil characteristics and expected behaviors such as evaporation, dispersion in the water column, and changes in oil density and a viscosity [34].

2.2.1 Description of the two- modeling models

WebGNOME is the Web-based interface to GNOME, a publicly available model for predicting oil spill trajectory and fate that simulates oil movement and weathering due to winds and currents. The NOAA Office of Response and Restoration (OR&R) Emergency Response Division created GNOME for oil spill response [61, 48]. NOAA's oil weathering model is ADIOS (Automated Data Inquiry for Oil Spills). It is an oil spill response tool that simulates how various types of oil weather (change physical and chemical properties) in the marine environment. ADIOS quickly estimates spilled oil's expected characteristics and behavior using a database of over a thousand crude oils and refined products.

The forecasting tool webGNOME was used to investigate the processes influencing the fate and distribution of marine pollution, particularly oil slick drift. It was also tested against many oil spill observations [8, 51]. It is an interactive environmental simulation system for rapidly modeling pollutant trajectories in the marine environment and a planning tool for examining hypothetical scenarios. This model is based on a Langrangian discrete element and can simulate the behavior of an oil spill [8]. WebGNOME has been utilized by emergency responders on behalf of industry, government, and groups to track oil spills, chemical spills, marine debris, and other incidents. They are intended to be a versatile trajectory model that specialists and the general public may use to guide cleanup activities and preventative measures [17].

2.2.2 Case study: simulation of a slick oil drift in the Gulf of Arzew

Dots represent the spilled oil on the map, called spots for the simulation. webGNOME includes uncertainly in particle transport. Each element integrated into webGNOME, i.e., wind, currents, pollutants, its drift, and evaporation, was treated with specific mathematical equations:

Drifters: Calculating zonal, meridional, and vertical displacement by moving pollutants.

$$\Delta x = \left(\frac{\frac{U}{111,1200024} \times \Delta t}{\cos(y)} \right) \times \Delta t;$$

$$\Delta y = \left(\frac{V}{111,12000024} \right) \times \Delta t; \ \ \Delta z = 0 \tag{1}$$

where, U is the speed of currents and winds (east–west); V is the speed of currents and winds (North–South); Y is the latitude in radians; Δy, Δx are the two-dimensional movements in latitude and longitude of currents and winds;

$\Delta t = t - t_1$ is the time between two steps; Δz is the vertical movement (in-depth); 111.12000024 is the number of meters per one (1) degree of latitude; 1 nautical mile equals 1 degree everywhere.

The distribution of the oil slick: Classical equation for the distribution of oil slick

$$\frac{\partial c}{\partial t} = D\nabla^2 C \tag{2}$$

where, C is the concentration of the spilled quantity, and D is the coefficient of the distribution mentioned in Eq. (3), written as follows:

$$\frac{\partial c}{\partial t} = Dx \times \frac{\partial^2 C}{\partial x^2} + Dy \times \frac{\partial^2 C}{\partial y^2} \tag{3}$$

Equation (3) gives the drift of the slicks in Cartesian coordinates, where, Dx, Dy are scalar diffusion coefficients in the x and y directions, and T is the time.

The diffusion coefficient is half the variance of the distribution of each step divided by the time step:

$$Dx = \frac{1}{2} \times \frac{\delta^2 x}{\Delta t} \tag{4}$$

2.3 The input data and boundary conditions

2.3.1 Winds in the region of Arzew

The study is based on the series of daily maximum wind speeds measured at the station of Arzew during the period 1986–2008 (Figs. 7, 8) provided by the NCC,
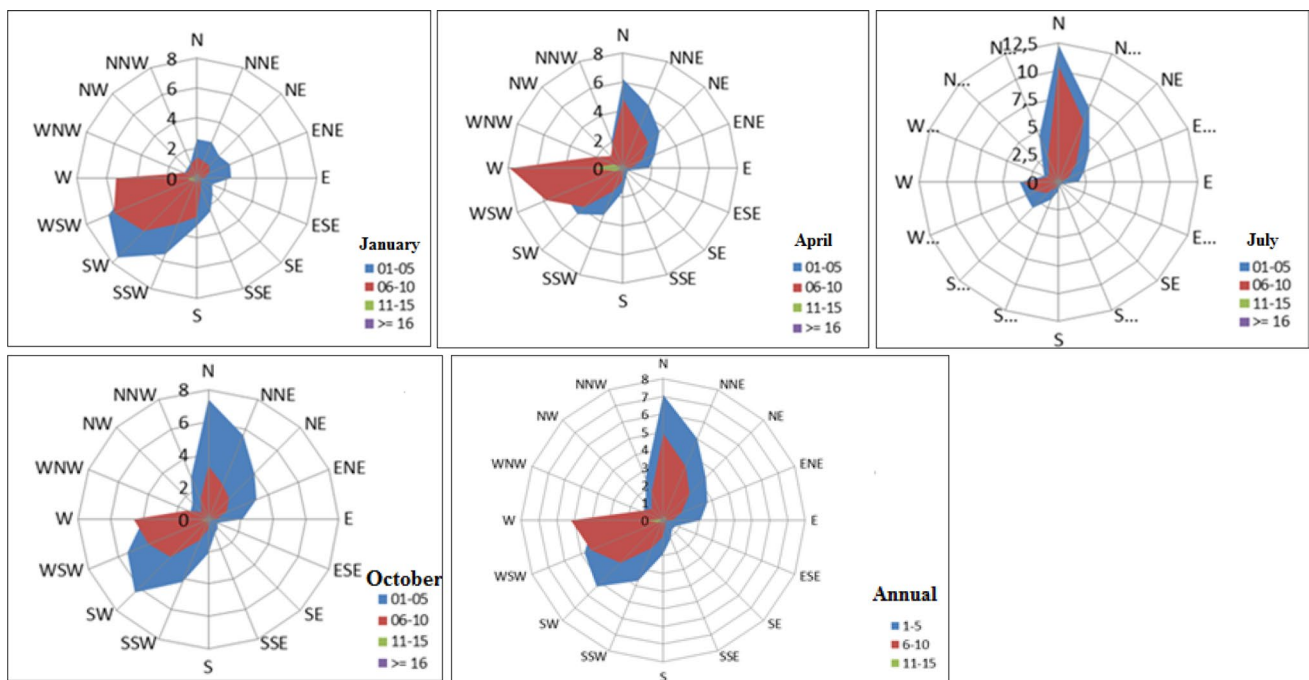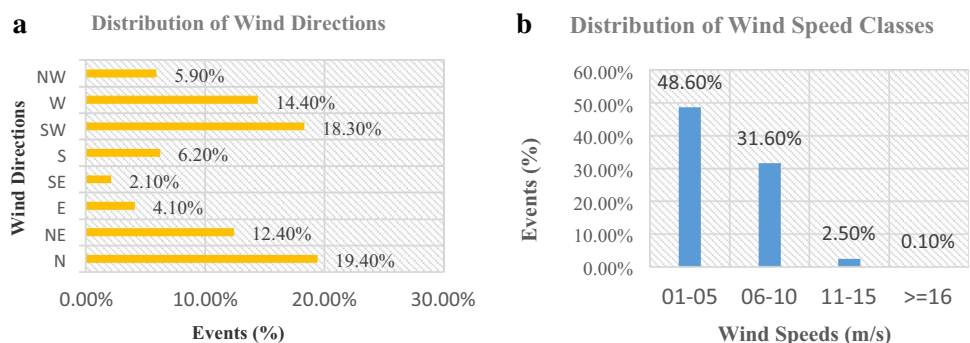

Fig. 7 Annual wind roses and months (January, April, July and October) in the Gulf of Arzew (1986–2008)

Fig. 8 **a** Distribution of wind direction. **b** Distribution of wind speed classes (1986–2008)
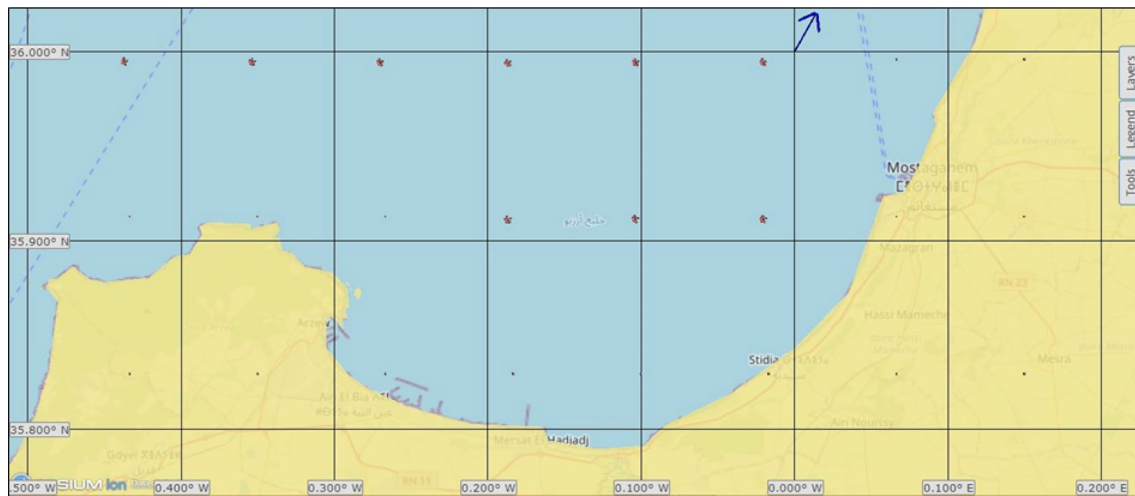
Fig. 9 The study area via GOODS and Integration in the webGNOME software

coming from the station of Arzew. Calm and moderate winds characterize this station in the autumn and spring seasons. The dominant wind directions are North and Southwest, appearing annually. About 48.6% of the winds are between 1 and 5 m/s, 31.6% between 6 and 10 m/s, and 2.5% between 11 and 15 m/s. The most frequent speeds are those between 1 and 5 m/s (Fig. 7) [61].

The data show that in January, calm winds of speed $1 < F(m/s) < 5$ are from the Southwest (SW) direction, as well as winds of speed $6 < F(m/s) < 10$ from the west-southwest (WSW) direction. For April, the wind force between 6 (m/s) and 10 (m/s) is in the West direction and is the most predominant. It is in the North direction for $01 < F(m/s) < 05$. In July, the wind direction is North, with a very high scale for $01 < F(m/s) < 05$ and $06 < F(m/s) < 10$. The winds in October represent a variation between two directions North and South West (SW) [36].

2.3.2 Surface sea currents

At the level of the Gulf of Arzew, the currents are oriented mainly toward the East. These currents flow 20–30 cm/s off Mostaganem, 40 km from the coast, and at 50 m depth. At the level of Arzew, a branch of this current enters the Gulf. Under the effect of the Coriolis force, currents appear clockwise, and their speed is very low (8 to 10 cm/s) [16]. Reliable oceanographic data are integral to oil spill vulnerability mapping and form the basis for accurate forecasting. Table 3 presents the different data sources integrated with webGNOME software. We studied local climatology and drew some idealized cases. For the different simulations, we created the actual data file using the dialog boxes, variable wind, spill information, temperature and salinity of the sea surface. These accurate data were obtained from the meteorological station of Arzew and the outputs at sea (in situ data).

The wind speed, direction, and values are integrated manually using dialog boxes under the webGNOME software. The current sea data is integrated from the real-time

Table 3 WebGNOME Model inputs and sources

| Inputs	Sources	Resolution spatial/temporal
Location file	https://gnome.orr.noaa.gov/goods (BNA map file format, Fig. 9)	50 m 30 days
Current data	The real-time RTOFS Global Ocean Model based on the HYCOM model	horizontal resolution 1/12 degrees
Horizontal Diffusion	webGNOME default value	–
Wind data	Provided by the National Climatological Center (NCC) and the weather station of Arzew. (Fig. 10)	Actual data
Sea surface temperature	Sea trips 2013–2018	Actual data
	MODIS satellite images (Level2_LAC) 2013–2022 processed under SeaDas (oceancolor.gsfc.nasa.gov)	250 m 1 day
Spill info	ADIOS Oil Database	Actual data
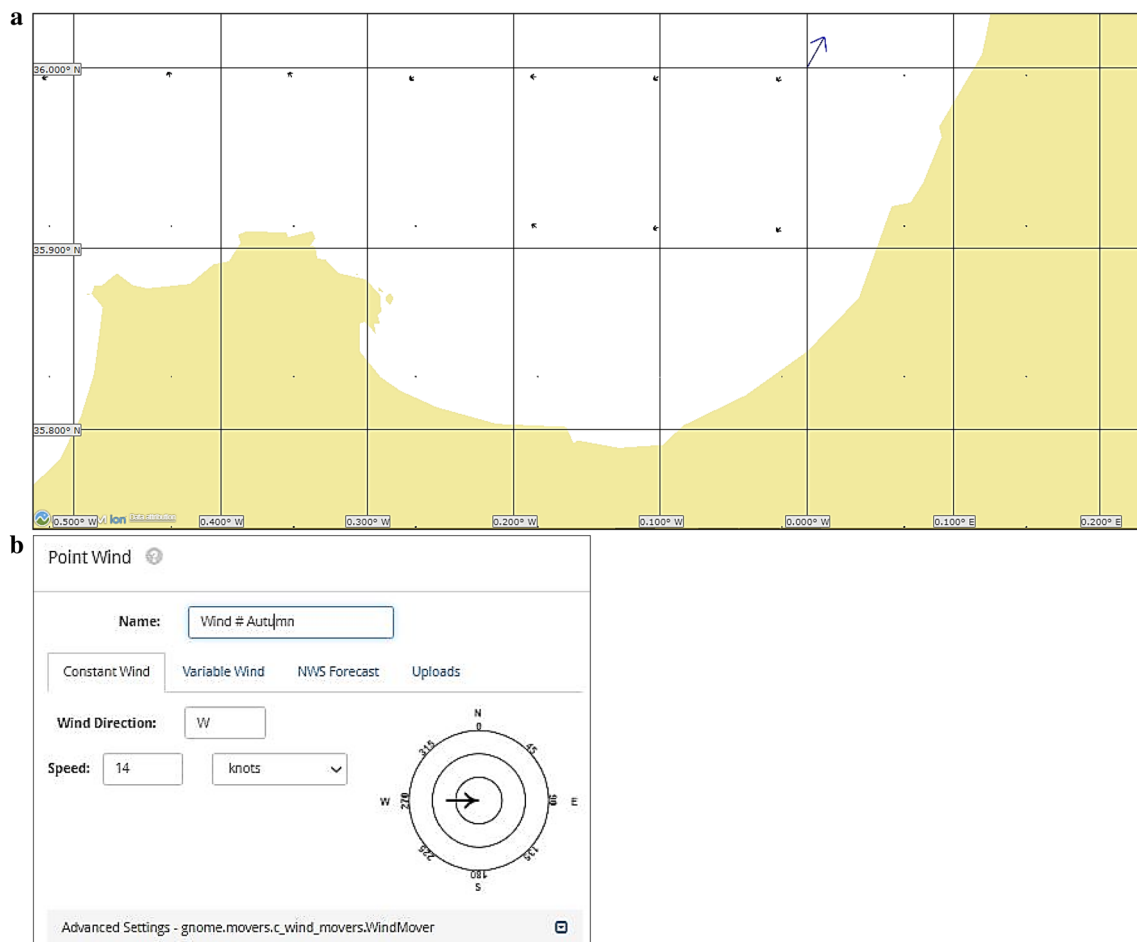
Fig. 10 **a** Visualization of the wind direction and current in the golf of Arzew 2022 under webGNOME. **b** The wind rose with the wind speed in 2018

RTOFS Global Ocean Model with a horizontal resolution of 1/12 degrees based on the HYCOM model (Fig. 10) [61].

2.3.3 Spilled oil properties

The main physico-chemical characteristics of the studied oils Algerian Blend and Algerian condensate Statoil, from the southern Algerian fields, are classified among lighter crude oils according to the values of their density respectively d = 0.8015 g/m^3, d = 0.707 g/ m^3; their degrees of API American Petroleum Institute is 44.87 and 68.4 [29]. It contains a relatively high proportion of light hydrocarbons. Crude with a shallow sulfur content of less than 0.1% and asphaltene, low acidity, low viscosity variation of (2.324 cSt (centistokes) at 20 °C and 1.996 cSt at 37.8 °C), (0.64 cSt at 20 °C and 0.54 cSt at 40 °C), and the values of the pour point (−36 °C, −45 °C) indicates that they are paraffinic. For Algerian Blend oil, the predominance of kerosene explains its high molecular weight of 225 g/mol (saturated aliphatic hydrocarbons or alkanes). The general chemical formula is

C11 H2n + 2. The energy products present in this oil have a better combustion quality (LPG 25%; Naphtha (C6 -C7) 34%; Kerosene (C12-C18) 12%; Gas-Oil (C18) 25%; Residue 25%).

2.4 Modeling scenarios

This section describes the decision criteria for the many tests of the various scenarios in the Gulf of Arzew. Table 4 displays the meteorological and hydrodynamic variables for the 16 scenarios investigated. For the year's four seasons of 2018, 10,000 metric tons of Algerian Blend crude oil spilled on two different spill spots (P1 and P2) in the Gulf of Arzew. And 30,000 metric tons of Algerian condensate Statoil, as well as the position of the two spill spots (P1 and P2) in the center of the Gulf of Arzew for the four seasons of 2022, as well as the model start time, model end time, simulation duration, and sea surface temperature and salinity.

Table 4 Initial conditions of the 16 scenarios studied (2018 and 2022)

Scenarios	2018				2022			
Seasons	Winter	Autumn	Summer	Spring	Winter	Autumn	Summer	Spring
Date	04/01/2018–06/01/2018	13/04/2018–15/04/2018	12/08/2018–14/08/2018	12/10/2018–14/10/2018	04/02/2022–06/02/2022	15/05/2022–17/05/2022	25/06/2022–27/06/2022	25/11/2022–27/11/2022
2 Points of the spills (P)	P1 = (35°54′5″ N and 0°8′18″ W) + P2 = (35°59′37″ N and 0°8′35″ W)							
Oil type	ALGERIAN BLEND				ALGERIAN CONDENSATE STATOIL			
Quantity	10,000 metric tons				30,000 metric tons			
Model start/end time	8 am to 8 am				1 pm to 1 pm			
Duration	24 h/48 h							
Wind speed (knot)/ direction	15 Nord	14 West	11 Nord	8 North–West	13 Nord	14 West	10 Nord	6 North–West
Salinity (PSU)	37	37	37	37	37	37	37	37
Sea temperature (°C)	14	20	25	18	15	21	24	19
Sea current	The real-time RTOFS Global Ocean Model with a horizontal resolution of 1/12 degrees based on the HYCOM model							
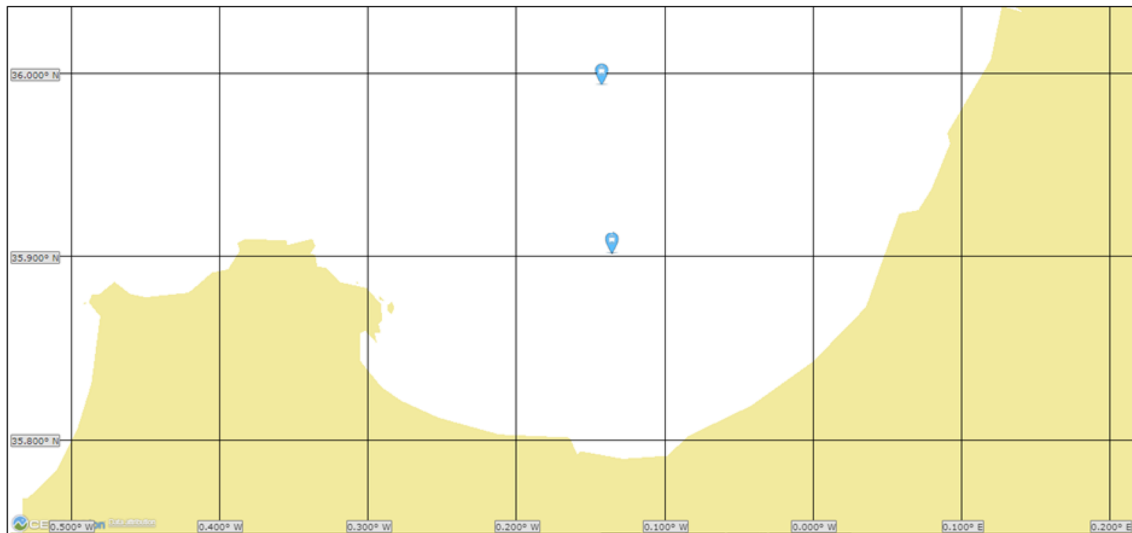
Fig. 11 Spill sites of the hydrocarbon slick in the center of the golf of Arzew (P1(35°54′5″ N et 0°8′17″ W), P2(35°59′37″ N et 0°8′35″ W)) under webGNOME

The discharge points (Fig. 11) are chosen based on our study area's density map of maritime traffic. The map shows heavy maritime traffic in the bay of Arzew at the level of coastal areas going to the sea (the meeting point of ships entering and leaving the bay presents the place of greatest danger at the entrance of the bay to the center of the Gulf of Arzew, hence the choice of the points of discharge of hydrocarbons for the study scenarios). The large capacity for the export of hydrocarbons in this area justifies this choice. The risk of events is omnipresent, and this pressure directly affects the marine environment.

3 Results and discussion

This section presents the results from the different tests of the different scenarios in the Gulf of Arzew for the 4 seasons of 2018 and 2022. A quantity of crude oil spilled of 10,000 metric tons of ALGERIAN BLEND type and 30,000 metric tons of ALGERIAN CONDENSATE STATOIL type, after 48 h of the spill (Table 4), with 2 points of the spills (35°54′5″ N and 0°8′18″ W), (35°59′37″ N and 0°8′35″ W) in the Arzew bay (Fig. 11). This study simulated hypothetical oil spill scenarios off Arzew Bay

using webGNOME and NOAA ADIOS, showing negative impacts on coastal areas. The results of the oil spill trajectories and alterations were discussed in this section.

Figures 12, 13, 14, 15 depict the oil concentrations at the surface as a function of particle density 48 h after the oil spill for the various scenarios tested. The preset color scale based on the Bonn Appearance (oil appearance at different thicknesses or concentrations) was used because concentration maps were a more effective representation. Moreover, it shows the uneven distribution of hydrocarbons while clearly illustrating high-concentration regions containing most of the oil. After superimposing the results of various scenarios, we present the trajectories of the oil slick, the most likely areas to be reached in the various possible cases, and the various physical and chemical changes that occur when oil is spilled in the marine environment.

The results of the various winter scenarios 2018 simulations show that for a wind speed of 13 to 15 knots North, the oil slick type ALGERIAN BLEND spilled in the two points P1 and P2 and moved towards the center of the bay of Arzew in the first hour. After 24 h of a spill at point P1 near 11, 40 km of coastline was affected, with a beached quantity of 7.3%, equivalent to 363 metric tons of oil, 62.8% of the spilled quantity evaporated, equivalent to 3139 mt, and a natural dispersion of 0.6%, equivalent to 29 mt, and 29.3% floating, equivalent to 1467 mt. However, after 48 h (Fig. 12a), the oil slick moved to the West, affecting 14.93 km of coastline with a stranded quantity of 20.6%, equivalent to 1895 metric tons of oil, an increase in evaporation to 64.1% of the quantity spilled, equivalent to 6156 metric tons, a natural dispersion of 57 mt, and 14.6.3% floating, equivalent to 1489 metric tons. However, after 24 h, the oil slick at point P2 continues to move without beaching (beached 0%), with a similar amount of evaporation and natural dispersion as the spill at point P1 of 62.8% and 0.6%. We notice that the oil slick begins to beach at a rate of 0.1% after 36 h, and after 48 h (Fig. 12b), 4.6% are stranded, equivalent to 436 mt or nearly 29.60 km of the coast was affected, and areas affected are (beach). Sidi Mansour, Mers El Hadjadj, the beautiful beach of Pont aux Poules, El Mecta, Bethioua, Ain El Bia, Arzew, and Cape Carbon are all nearby.

The simulation model of hydrocarbon ALGERIAN CONDENSATE STATOIL, for winter 2022, with a volume of 30,000 metric tons, shows that after 24 h, the slick moves westward without stranding in the two points of spill P1 and P2, with 84.1% evaporation, 12% sedimentation, and 3.7% floating. After 48 h of spillage at point P1 (Fig. 12c) and at point P2 (Fig. 12d), the oil slick beached on nearly 28 km of the Gulf of Arzew's western coast, and areas affected are (beach): Sidi Mansour, Mers El Hadjadj, the beautiful beach of Pont aux Poules, El Mecta, Bethioua, Ain El Bia, Arzew, and Cape Carbon. The volume evaporated is 83.9%,

equivalent to 13,022 mt, with natural dispersion of 13.9%, 1889 mt, sedimentation of 0.1%, 23 mt, and floating of 2.1%, equivalent to 546 mt.

The results of the various modeling scenarios for the winter season for 2018 and 2022 show that the coastal areas of central and western Arzew, such as Pont aux Poule, Betioua, Arzew, and Cap Carbon, are the most likely to be reached by the oil slick. These areas are highly sensitive to the oil spill (Fig. 6 represents the balance of the maps of the coastline's physical, socio-economic, and biological sensitivity). Because they are areas of artificial reef implementation, Cap Carbon and Pont aux Poule are classified as essential areas with a low resistance to protection, whereas Sidi Mansour, Mers El Hadjadj, and Ain El Bia are classified as high sensitivity.

For the autumn 2018 scenarios, for a 14-knot westerly wind speed, with a spill volume of 10,000 mt of the ALGERIAN BLEND type, which started on April 13, 2018, at 8 am and lasted 48 h until April 15, 2018, at 8 am, the results of the simulations showed that after 24 h of the spill at point P1, the oil slick moved towards the East and for the spill at point P2 the slick moved towards the North-East without beaching in both cases. After 24 h, the evaporation rate is 64.2%, or 3208 mt, with a natural dispersion of 0.6%, or 30 mt, and floating equally to 35.2%, or 1761 mt. After 42–48 h, a portion of the oil slick at point P1 (Fig. 13a) beached on the North-East coast near Cap Ivi in Mostaganem, affecting approximately 11.90 km, with an evaporation rate of 67%, equivalent to 5716 mt and a quantity of 57 mt (0.6%) dispersed naturally and 31.3% floating equivalent to 2818 mt with 0% sedimentation. Even after 48 h, the oil slick from the P2 (Fig. 13b) spill continues to move northeastward toward the open sea without beaching (Beachede 0%), with similar dispersion and floating evaporation rates as the P1 spill.

The scenarios began on May 15, 2022, at 1 pm and ended on May 17, 2022, with a volume of 30 000 metric tons of ALGERIAN CONDENSATE STATOIL. After 24 h, the oil slick moved towards the North-East for the two spill points P1 and P2, in the same direction as the slick followed in the autumn 2018 scenario, without beaching (Beached 0%), with an evaporation rate of 87.5% equivalent to 13,118 mt. After 48 h, a large portion of the oil slick beached on the north-east coast of Mostaganem noting (Mazagran, Oureah beach to Stidia) on approximately 19.40 km (Fig. 13c). However, only 8.20 km of the coast was affected by the spill at point P2 (Fig. 13d), always on the northeast coast of Mostaganem, with an evaporation rate of 87.3%, equivalent to 25,922 mt, natural dispersion of 10.8%, equivalent to 3289 mt, floating of 2.2%, equivalent to 548 mt, and very low sedimentation of 0.1%, equivalent to 17 mt. For the autumn 2018 and 2022 scenarios, the most likely areas to be reached by oil spills are the

Fig. 12 Winter 2018 and 2022 oil spill scenarios: **a** After 48 h in point P1, 2018; **b** After 48 h in point P2, 2018; **c** After 48 h in point P1, 2022; **d** After 48 h in point P2, 2022
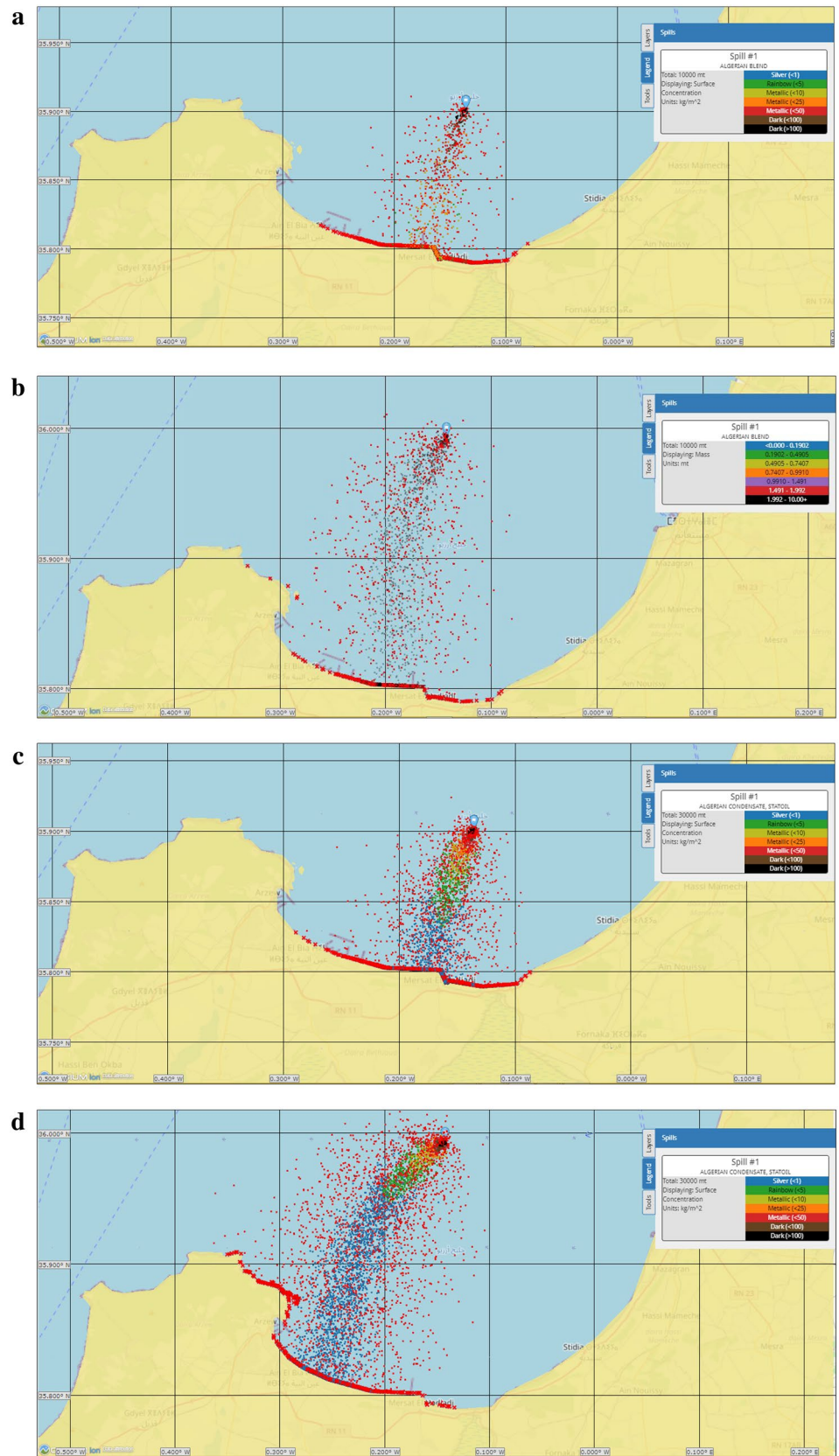
Fig. 13 Autumn 2018 and 2022 oil spill scenarios: **a** After 48 h in point P1, 2018; **b** After 48 h in point P2, 2018; **c** After 48 h in point P1, 2022; **d** After 48 h in point P2, 2022

Fig. 14 Summer 2018 and 2022 oil spill scenarios: **a** After 48 h in point P1, 2018; **b** After 48 h in point P2, 2018; **c** After 48 h in point P1, 2022; **d** After 48 h in point P2, 2022
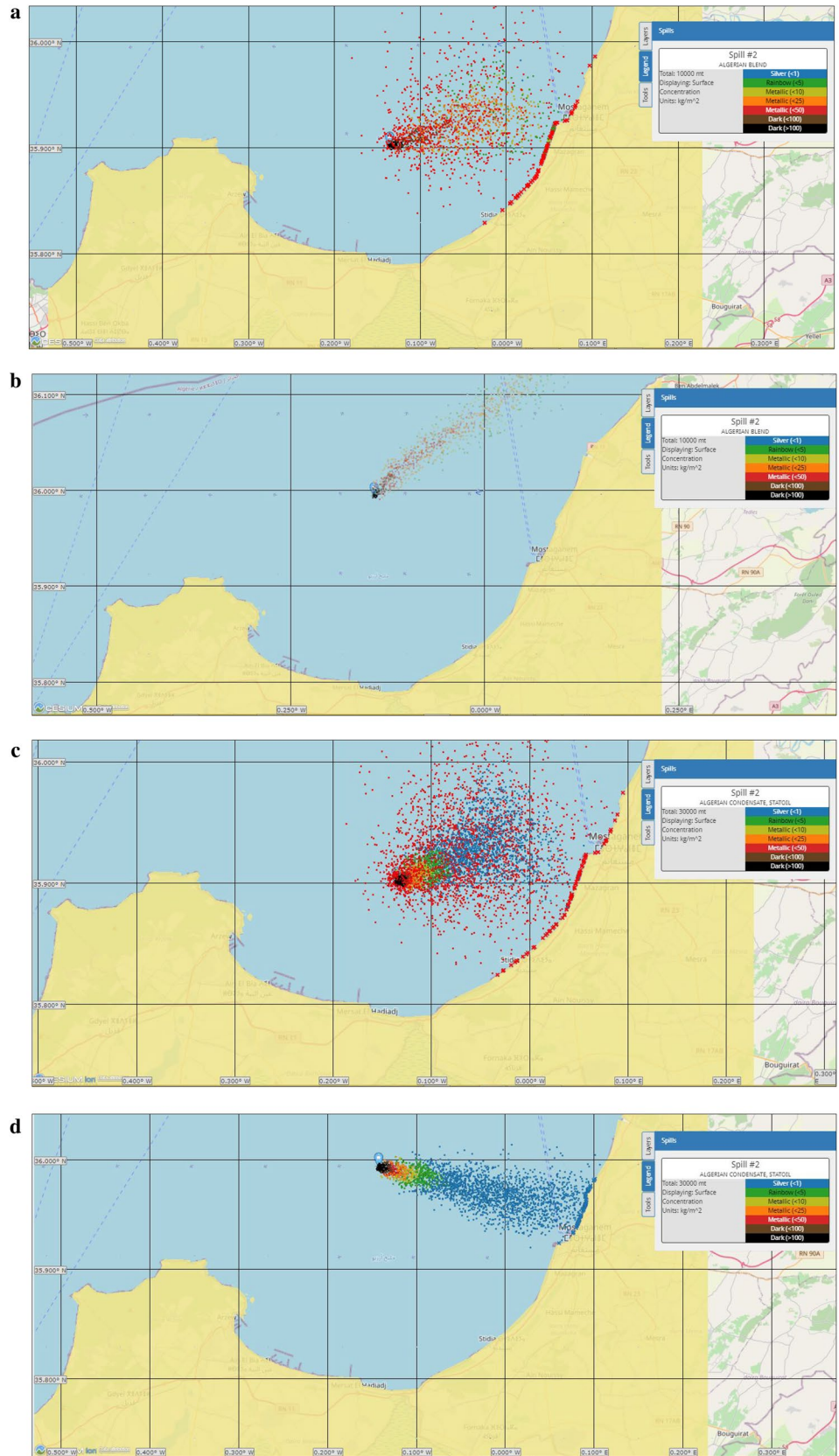
Fig. 15 Spring 2018 and 2022 oil spill scenarios: **a** After 48 h in point P1, 2018; **b** After 48 h in point P2, 2018; **c** After 48 h in point P1, 2022; **d** After 48 h in point P2, 2022
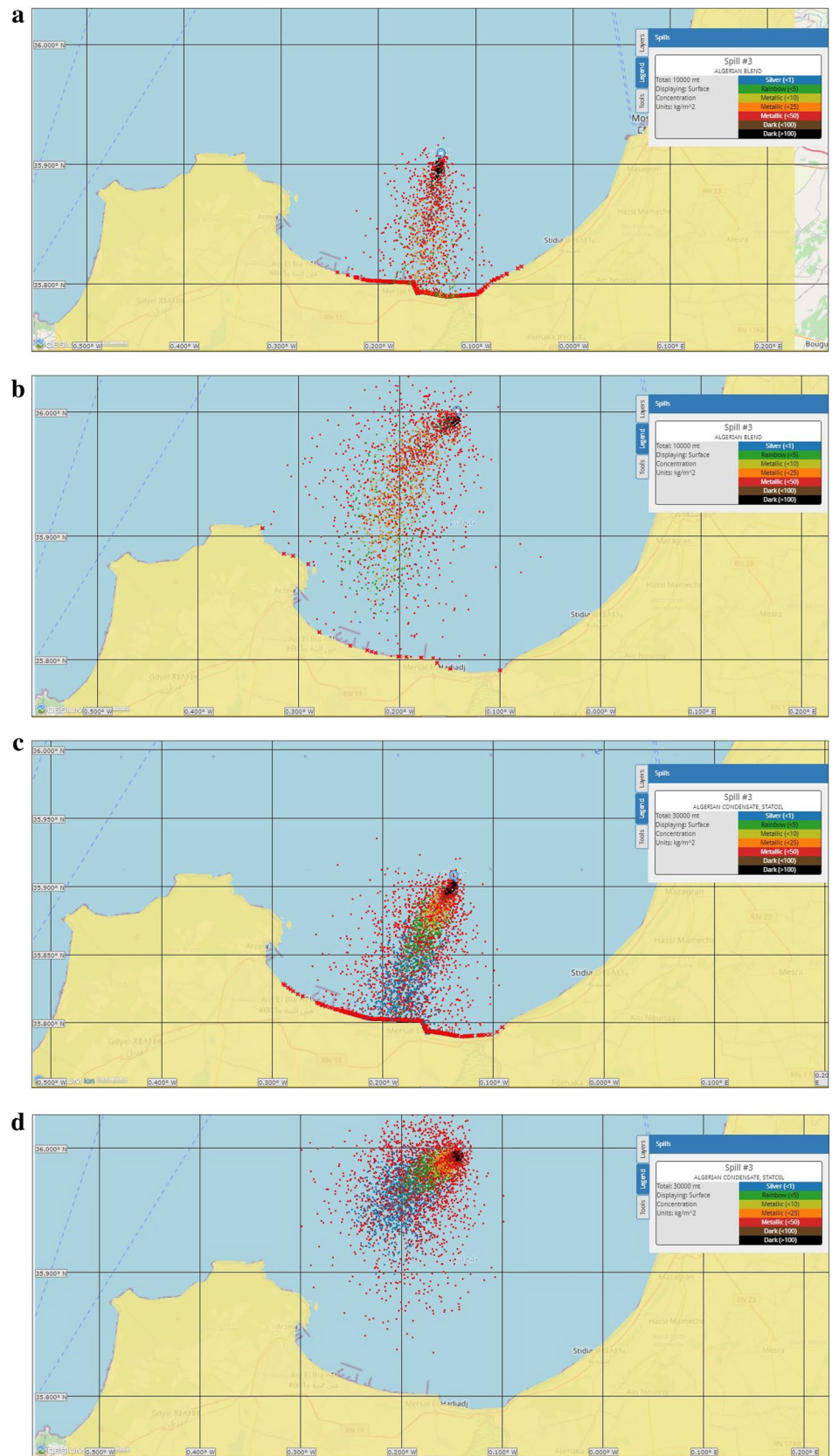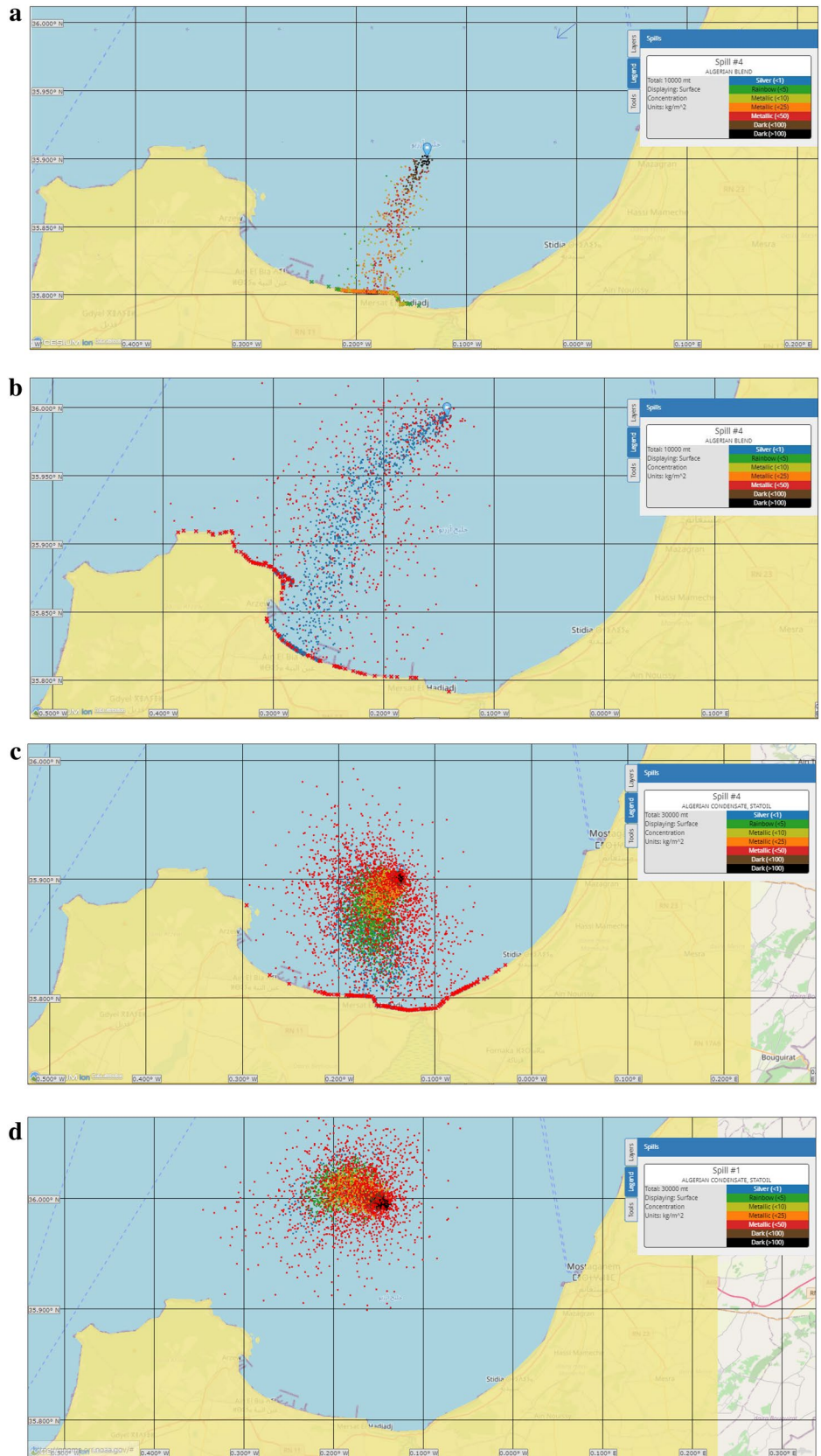
northeast coast near Cape Ivi in Mostaganem, Mazagran, Oureah beach up to Stidia, classified as medium sensitivity areas with medium resistance to oil spills.

In the summer scenarios, beginning at 8 am on August 12, 2018, and lasting 48 h until August 14, 2018, at 8 am, we can see that for a speed of 11 knots North and a volume of oil type ALGERIAN BLEND of 10,000 mt, we can notice that for a speed of 11 knots and a volume of oil type ALGERIAN BL (Table 4). After 24 h, the oil slick at point P1 moved towards the center of the Gulf of Arzew, affecting approximately 14.48 km of the coast (Sidi Mansour Beach, El Mectaa Beach to Mers El Hadjadj and Pont aux poules). After 24 h, the oil slick at point P2 moved to the West of the Gulf of Arzew without beaching, with wind speeds lower than during the winter and autumn seasons and a sea surface temperature higher than 25°c, with an evaporation rate of 65.8%, equivalent to 6422 mt, a natural dispersion of 0.5%, equivalent to 40 mt, and a floating quantity of 33.7%, equivalent to 2361 metric tons. The oil slick moved towards the center and West of the Gulf of Arzew after 48 h of spillage for the two spill points. Affecting nearly 17.60 km of coastline for the spill at point P1 (Fig. 14a), (Lilou Beach, Sidi Mansour Beach, Mectaa Beach, Mers El Hadjadj, Pont aux Poule, and the LNG port of Bethioua), and approximately 29.70 km from the coast for point P2 (Fig. 14b), affecting all areas affected by the spill at point P1 plus Arzew with a very small amount of oil beached). With an evaporation rate of 68.9% (6633 mt), natural dispersion of 0.5% (50 mt), and floating of 35.6% (2867 mt).

For the summer simulations, on June 25, 2022, at 1 pm, with a duration of 48 h until June 27, 2022, at 1 pm, at the two discharge points, with a volume of 30 0 00 metric tons of ALGERIAN CONDENSATE STATOIL and a North wind speed of 10 knots. We noticed that after 24 h, the oil slick had moved toward the center and West of the Arzew golf course. Regarding summer 2018 scenarios, the spill at point P1 affected nearly 8.9% of the coast, and the affected areas are listed below (Sidi Mansour Beach, Mectaa Beach, Mers El Hadjadj, Pont aux Poule). The spill at point P2, on the other hand, after 24 h, the oil slick moved to the West of the Gulf of Arzew without beaching, with an evaporation rate of 90.4% equivalent to 13,713 mt, a natural dispersion of 4.2% equivalent to 635 mt, and floating of 5% equivalent to 741 mt in the two points of similar spills. The oil slick touched nearly 21.58 km of the central and western coast of the Gulf of Arzew after 48 h of spillage, as shown in Fig. 14c, for the spill at point P1. However, the slick at point P2 (Fig. 14d) continues to move west of Arzew without beaching, with an evaporation rate of 89.9%, equivalent to 2,6983 mt, natural dispersion of 8%, equivalent to 2,410 mt, and floating of 2.1%, equivalent to 603 mt. According to the summer 2018 and 2022 scenarios, the most likely areas to be reached by oil spills are

the central and western coastal areas, such as Lilou Beach, Sidi Mansour Beach, Mectaa Beach, Mers El Hadjadj, Pont aux Poule, the Bethioua methane port, and Arzew, which are classified as areas of very high sensitivities and high sensitivity to the spill of the oil slick.

The simulations for the various spring 2018 scenarios begin on October 12, 2018, and run for 48 h until October 14, 2018, at 8 am, with an NW wind speed of 8 knots and a sea surface temperature of 18 °C, 10,000 metric tons of ALGERIAN BLEND spilled on the two different spill points, P1 and P2. After 24 h for the spill at point P1, the oil slick moved towards the West of the Gulf of Arzew, and about 5.61 km of the coast was affected (Beached of 3. 9%), and the area of Mers El Hadjadj was affected, for the spill at point P2 the oil slick also moved westward, but without beaching, the amount evaporated after 24 h is 63.8% equivalent to 3188 mt, a natural dispersion of 0.3% equivalent to 14 mt, and floating of 36% equivalent to 1798 mt. The oil slick touched nearly 9.35 km of the west coast of the Gulf of Arzew (Mers El Hadjadj to the port of Betioua) after 48 h for the spill at point P1 (Fig. 15a) and nearly 28.34 km of the west coast of the Gulf of Arzew (from Mers EL Hadjadj to Port of Bethioua, Arzew and Cape Carbon), for the spill at point P2 (Fig. 15b), with 66.9% evaporation equivalent to 6665 mt, 0.3% natural dispersion, and 27.8% floating equivalent to 2775 mt.

The simulations for the spring 2022 scenarios begin on November 25, 2022, and end on November 27, 2022, at 1 pm for 48 h. With an NW wind speed of 6 knots and a sea surface temperature of 19 °C, 30,000 metric tons of ALGERIAN CONDENSATE STATOIL spilled on the two different spill points, P1 and P2. After 24 h, on November 26, 2022, at 1 pm, the oil slick at point P1 moved towards the center of the Gulf of Arzew without beaching, and the oil slick at point P2 moved towards the north-west of the Gulf of Arzew in the direction of the open sea, with 88.9% evaporation, 0.7% natural dispersion, and 10.3% floating. After 48 h of spillage at point P1 (Fig. 15c), the oil slick beached in the center of the Gulf of Arzew, affecting approximately 19.70 km of coastline (from Stidia, Sidi Mansour beach, Port aux Poule, and Mers El Hadjadj). On the other hand, the slick continues to move toward the open sea in the spill at point P2 (Fig. 15d). After 48 h, the evaporation rate for the two spill points, P1 and P2, is approximately 92.4%, or 17,158 mt, with a natural dispersion of 2%, or 72 mt, and floating of 5.6%, or 1635 mt.

According to the winter scenarios for 2018 and 2022, the most likely areas to be reached by oil spills are the central and western coastal areas such as Pont aux Poule, Arzew, and Cap Carbon, which are classified as areas of very high sensitivities, as well as Sidi Mansour beach, Mers El Hadjadj, and the port of Betioua, which are classified as areas of high sensitivities. Because it is impossible

to present all possible scenarios, the scenarios for 2018 and 2022 were limited to 16. Wind forcing has a significant influence on particle release along the Arzew coast, according to Duran Rodrigo (2018). This force appears to be the only one capable of generating and maintaining the observed coastal currents. Particle trajectories change as seasonal winds change [47, 54].

During the various hypothetical simulation scenarios, the evaporation of ALGERIAN BLEND and ALGERIAN CONDENSATE STATOIL crude oil accounted for more than 60% of the two-day volume reduction. The rest of the oil, on the other hand, maintained sufficient buoyancy to remain on the surface of the water, as demonstrated by the results of the various simulations, because the two types of oil have very high API (American Petroleum Institute) densities of 44.87 and 68.4, respectively, indicating that they float on the water form a very thin film on the surface of the water, increasing their exposure to the environment and, as a result, weathering processes such as evaporation and dispersion. ALGERIAN CONDENSATE STATOIL exhibited higher evaporation and natural dispersion rates during the simulations than ALGERIAN BLEND. Evaporation was also found to increase with slickness, temperature, and wind action.

If the time to impact is greater than 24 h, the fraction of mass stranded is small in most scenarios. As a result, the magnitude of the environmental risk is determined by the length of time the oil spends at sea, as confirmed by the Nagheeby and Kolahdoozan study [46]. The dominant wind direction for the study area is southwest in the winter, west in the autumn, and North in the summer and spring. The movement of the oil slick confirms that the wind is the driving force, with the slick moving south to the center of the coastal area in winter and East to Mostaganem in autumn scenarios. During the summer and spring, the slick only moved to the West.

The amount and direction of the oil spill at various time intervals following the accident are critical for determining the best response method [49]. As a result, the system finally provides the output of the response argument variations, the timing, and the direction of use. The system specifies the location and quality of the skimmer and booms on behalf of the coastal management authority in charge of responding to the accident. This intervention system will be especially useful in waterways near sensitive areas where oil transport is dense, such as Arzew and Bethioua. In these sensitive areas, the responsible coastal authority must make the most accurate and timely decisions in accident response management. After recognizing the importance of modeling as a critical tool in combating marine pollution and changing seawater quality, and after running a series of scenarios, it became clear that wherever the oil spill in the Gulf of Arzew occurs, it will be a major disaster affecting the environment, tourism, and the economy. Because the depth is shallow and the currents are almost nonexistent, an accident causes quasi-significant pollution. NOAA's ADIOS simulation software was used to forecast the weathering of the spilled oil (Table 5) [47].

The ADIOS model results show the different weathering rates of the spilled oil, and WebGNOME also supports scenarios that only consider the oil weathering (similar to the previous NOAA ADIOS model), as shown in Fig. 16.

The results of the ADIOS model showed that Evaporation began immediately after the oil was spilled into the seawater for all 16 scenarios. About 40–45% of the oil spill evaporated in the first hour of the spill. After that, the evaporation rate gradually increased. It was found that after 5 days, the evaporation rate of the spilled quantities of the 16 scenarios varied from 74.7% to 79.8% of the spill quantity for ALGERIAN BLEND and 85.6% to 91.4% of the spill quantity for ALGERIAN CONDENSATE STATOIL, almost half of the amount of crude oil spilled evaporated. On the other hand, the natural dispersion rate was slow, starting after 1 h of the spill and reaching about 1% at the end of the simulation for ALGERIAN BLEND and about 13% for ALGERIA CONDENSATE STATOIL (Table 6). Therefore, oil spill responders could use this study as a reference or guide to inform

| Table 5 Integration of the initial conditions of the 16-oil spill scenarios in the ADIOS model (inputs)	Inputs in ADIOS	Spill scenario
	Oil	Type of oil or product spilled
		ALGERIAN BLEND/ ALGERIAN CONDENSATE, STATOIL
	Wind	Weather conditions
		Wind Speed (knots) = 15N/14W/11N/8NW/13N/14W/10N/6NW
	Water	Water properties
		Temperature = 14 °C/20 °C/25 °C/18 °C/15 °C/21 °C/24 °C/19 °C
		Salinity = 37 PSU
	Release	Release Information
		Time of release = 2018/2022
		Amount Spilled = 10,000 metric tons/ 30,000 metric tons
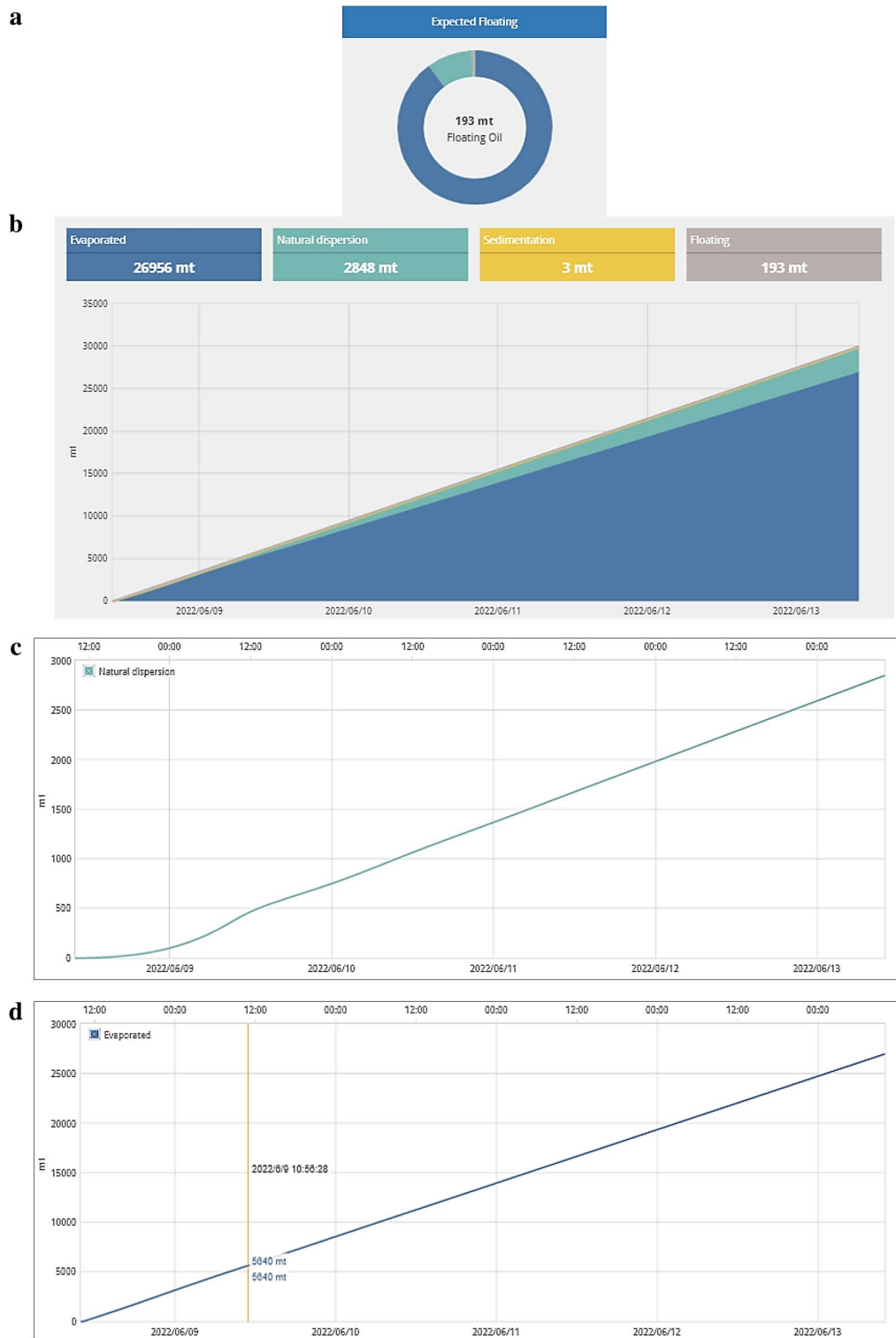
Fig. 16 ADIOS outputs of **a** the amount remaining, the amount dispersed and the spill evaporation oil rate within five days; **b** the expected floating oil, the amount evaporated, sedimentation and natural dispersion within five days; **c** the natural oil dispersion (ml) within five days; **d** the oil evaporation (ml) within five days; **e** the oil floating (ml) within five days; **f** the oil sedimentation (ml) within five days. Table 6 summarizes the amount of hydrocarbon spilled and the percentage of the various physicochemical processes used in the scenarios investigated
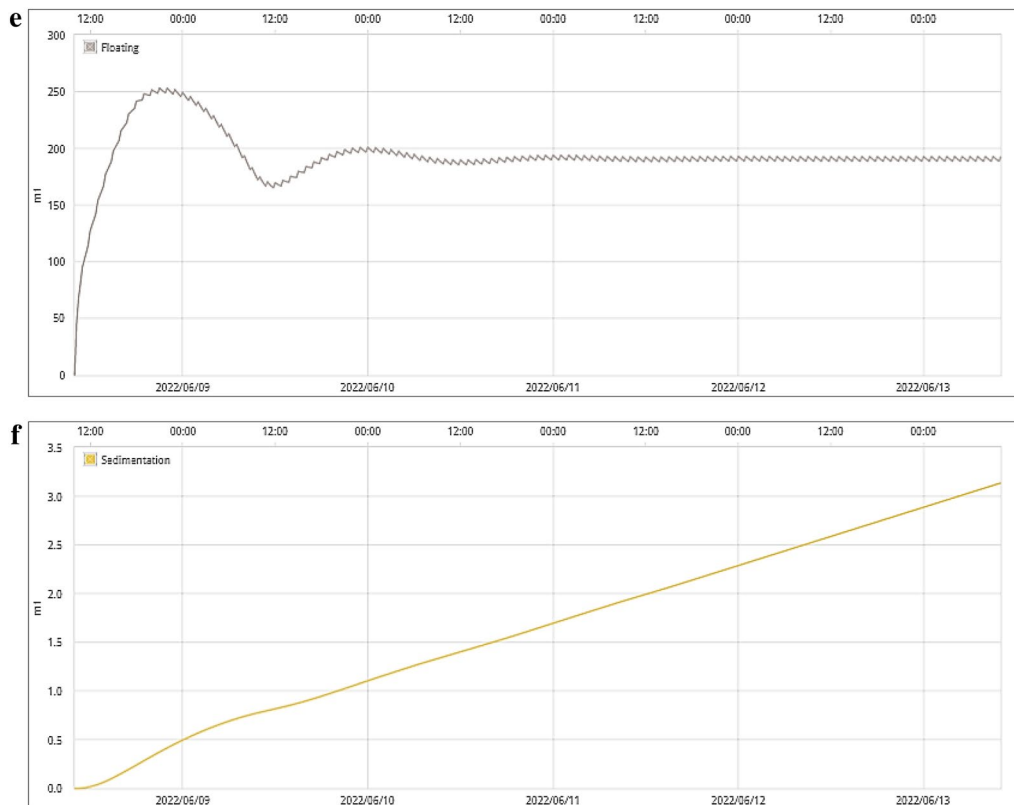
Fig. 16 (continued)

the systematic environmental conservation planning process near the Arzew coast.

3.1 Background to the spill and response decision

3.1.1 At sea

Given the evaporation rate of light crude oil, one of the most appropriate remedies for tiny spills is to allow the condensate spread out and evaporate naturally. The risk area, national rules, the probability of drift, and the potential environmental and socio-economic repercussions determine the definition of these modest volumes (a few m^3). For medium to large spills, the lightest hydrocarbons, which have an evaporation rate of more than 70%, similar to petrol and kerosene, have a low persistence while posing a high risk to responders (explosive environment). In this scenario, doing nothing and leaving things alone is advised.

3.1.2 In coastal areas

Pollution response operations should be carried out when the pollutant drifts towards the coast or ecologically or socio-economically sensitive areas, regardless of the volumes spilled (generally speaking, a slick move with the current and under the influence of the wind). It can be envisaged to protect these areas by booms, if possible fireproof. It is important to note that these measures involve the use of nautical means, which must therefore be employed well before the arrival of the pollutant. Dispersants or in-situ burning is necessarily more delicate than recovery, which must be prioritized. Geographical limits generally apply to using dispersants near the coast, sometimes qualified by the volumes spilled. In the case of burning, the first question is regulatory, as this technique is banned in many countries. In the case of a spill of the order of a few m^3, very close to the coast or on the coast, it may be possible, if the slick is naturally contained, to recover the pollutant after covering it with a carpet of low or medium expansion foam, to limit the formation of flammable vapors. Recovery will occur with a floating suction head adapted to recover the pollutant under the foam

Dates	Time (h)	Amount released (mt)	Evaporated (%)	Natural dispersion (%)	Sedimentation (%)	Floating (%)
Table 6 Evolution of the quantity spilled after 5 days for the 16 scenarios (oil balance under ADIOS model)						
04/01/2018–06/01/2018	1	80	40.9	0.4	0	58.7
	24	2000	64.5	0.9	0.1	34.5
	48	4000	67.9	0.9	0.1	31.2
	60	5000	69.4	0.9	0.1	29.7
	120	10,000	74.7	0.9	0.1	24.3
13/04/2018–15/04/2018	1	80	43.4	0.3	0	56.2
	24	2000	66.6	0.9	0.1	32.4
	48	4000	71.1	1	0.1	27.9
	60	5000	72.9	1	0.1	26.1
	120	10,000	77.7	1	0.1	21.3
12/08/2018–14/08/2018	1	80	45	0.2	0	54.8
	24	2000	69.3	0.8	0	29.9
	48	4000	74.6	0.9	0	24.5
	60	5000	76.2	0.9	0	22.9
	120	10,000	79.8	0.9	0	18.3
12/10/2018–14/10/2018	1	80	42	0.1	0	58
	24	2000	66.3	0.5	0	33.2
	48	4000	71.5	0.5	0	28
	60	5000	73.2	0.5	0	26.2
	120	10,000	77.7	0.6	0	21.7
04/02/2022–06/02/2022	1	240	56.1	0.4	0	43.5
	24	5970	85.6	11.1	0.1	3.3
	48	11,970	85.5	12.6	0.1	1.8
	60	14,940	85.6	13	0	1.3
	120	29,910	85.5	13.8	0	0.7
15/05/2022–17/05/2022	1	250	59.8	0.5	0	39.7
	24	6000	86.7	10.3	0.1	2.9
	48	12,000	86.8	11.7	0.1	1.4
	60	15,000	86.8	12	0.1	1.1
	120	30,000	86.8	12.6	0	0.6
25/06/2022–27/06/2022	1	250	60.5	0.2	0	39.3
	24	6000	90.2	6.7	0	3.2
	48	12,000	89.6	8.8	0	1.7
	60	15,000	89.5	9.2	0	1.4
	120	30,000	89.4	9.9	0	0.7
25/11/2022–27/11/2022	1	250	55.5	0	0	44.4
	24	6000	90.7	1.1	0	8.2
	48	12,000	92.8	3.5	0	3.8
	60	15,000	92.5	5.1	0	2.4
	120	30,000	91.4	7.4	0	1.2

mat. The storage tank must be secured by inserting it and ensuring no hot spots in the area. These operations must be carried out by trained professionals with appropriate personal protection (respiratory and skin protection. It is compulsory to wear a self-contained breathing apparatus in a confined atmosphere due to the abundance of gases released and to wear protective clothing covering the whole body as much as possible (face and eye protection: wear chemical goggles; skin protection: wear hydrocarbon resistant gloves). Personal respiratory protection equipment must be worn whenever there is a risk of inhalation of toxic vapors when concentrations approach the Mean Exposure Value (MEL = 200 mg/m^3). Self-adjusting threshold and oleophilic reclaimers are recommended for larger volumes, but their flammability may limit their use.

4 Conclusion

The rise in marine pollution caused by hydrocarbons worldwide warns of the possibility that these pollutants will persist in the environment and harm ecosystems and human health. This study focused on the Gulf of Arzew in Oran, where oil spills seriously threaten marine and coastal ecosystems. The goal is to identify the areas likely to be affected, predict when the oil will reach the coastline, and calculate the oil weathering processes (evaporation, natural dispersion, and floating percent). The parameterization of oil spill simulation and oil and transport processes varies significantly across the oil spill models studied. Nonetheless, almost all rely heavily on marine meteorological forcing. Arzew's coastal area is extremely vulnerable to oil spills owing to the frequent use and movement of petroleum products.

The type of oil used determines the characteristics, spread, alteration, and impact of an oil spill (NOAA 2020). In our study, the light crude oil types ALGERIAN BLEND and ALGERIAN CONDENSATE STATOIL evaporate relatively quickly, with the temperature of the oil being the primary determinant of evaporation. Within a few h, evaporation removes most of the oil's volatile fractions from the atmosphere, reducing the oil's toxicity in the marine environment. However, these compounds are transferred to the atmosphere, and the effects of evaporation can be more toxic in some cases (e.g., large spills near densely populated areas). Furthermore, the viscosity of the remaining stains rises (heavier oil components remain in the sea), causing severe physical and chemical effects on the marine environment. According to a study of coastal vulnerability to oil spills in the Gulf of Arzew, Cap Carbon, Arzew, and Pont aux Poules have extremely high sensitivity. As a result, this study cautions against future leaks that could harm these areas. According to simulation results, some spilled oil washed up on the Gulf of Arzew, while others remained at sea after 48 h. This behavior of oil in the water and on the coast (which is particularly vulnerable in some areas designated as areas in need of protection) raises concerns for the marine and coastal ecosystem, seawater quality, marine organisms such as seabirds and fish, and humans (heavily populated coastal areas). Therefore, it is necessary to act quickly to protect these organisms.

The wind, the main driver of marine currents in our study area, primarily forces the trajectories. The currents in the Gulf of Arzew are primarily oriented eastward, and the surface current plays a minor role. Their speed is very low (8–11 cm/s), whereas the winds are very fast, reaching up to 15 m/s in winter. Oil slicks move faster during the winter and autumn than during the summer and spring seasons. In inland circulation models, winds have been confirmed as the most important driving force. Wind and small-scale currents were the driving forces behind particle movement. The global oil spill modeling system is complete and ready for use in real time. Without entering details about the incident location or currents, the ADIOS model can estimate the spilled oil's characteristic expected value and behavior based on the spilled oil's physical properties and seawater.

The potentially polluted area is confined to areas within a 10 km*10 km zone around the wreck site due to the oil's rapid evaporation rate, and the contaminated area is closely associated with the surface wind. The properties of the spilled oil determine the polluted areas. Oil-contaminated water will likely spread offshore or onshore, causing short- and long-term damage. Model validation demonstrates that the models' outputs are highly accurate when the inputs are highly accurate. Mahmoud and Bagy [39] also reported this finding [60]. The findings of this study can be used to develop an effective contingency plan to mitigate the future effects of marine oil pollution in the Gulf of Arzew.

4.1 Recommendations

A technical collaboration between the Arzew port companies (PCA) and the Arzew meteorological station should be formalized through a framework agreement. As a result, weather forecasts for the affected area and oil slick drift maps will be available as soon as possible. In the event of an accident or illegal accident activity, a collaboration between national port agencies (Maritime Traffic) and a scientific database using Sentinel1 satellite images to detect oil slicks on the sea surface allows the detection of the ship responsible for the oil spill. Furthermore, it enables the enforcement of maritime traffic laws by correlating detected oil slicks with ship movement at the same time and place. Establish a development strategy and legal framework for this sector, increase investment, integrate new techniques, and conduct optimization studies to locate service stations near container doors to reduce the risk of accidents and oil pollution.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Competing interests The authors declare no competing interests.

Ethics approval and consent to participate This work did not report on or involved the use of any animal or human data or tissue.

Consent for publication This work did not contain data from any individual person.

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