JOURNAL OF MARITIME RESEARCH

Vol XIV. No. II (2017) pp 32–40

ISSN: 1697-4040, www.jmr.unican.es

Oil Spill Model and Response Tools: Analysis of oil spill risks due exploration and oil prospecting near the coast of the Canary Islands

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ARTICLE INFO

Article history:
Received 16 August 2017;
in revised form 16 August 2012;
accepted 24 August 2017.

Keywords:
Oil Spill Modelling, SIROCO, OILMAP, Canary Islands.

ABSTRACT

Through Oil Spill Model and Response System (OILMAP) and the Island Response and Operations System against Ocean Pollutants, in Spanish Sistema Insular de Respuesta y Operaciones Ante Contaminantes Oceánicos (SIROCO) it is possible to reproduce and analyse the behaviour and evolution of pollutant spills in the sea. This efficient planning and response system can be used operationally in emergency situations and for the planning of response to an oil slick. The present study analyzes the possible consequences derived from hypothetical accidental spills due to oil prospecting and drilling that affect the littoral of the Canary Islands.

1. Introduction.

The Spanish coasts have been the scene of big sea accidents with awful consequences for the environment as well as for sea resources and the economic use of coastal areas. The latest accident was the shipwreck of the Prestige (2002) which dealt to a spill of 63,200 tons of heavy oil-fuel with a serious coastal impact that evidenced the big scientific, technological and organizational challenge that prevention of sea accidents means for both the administration and the oil industry itself (PROTECMA, 2011).

Sea pollution has been under discussion in different forums and conferences worldwide with the objective of improving the security conditions in offshore oil rigs and to establish a variety of rules and procedures in order to prevent accidents that may cause an impact on the sea environment. In the last decade, the marine and environmental administrations have mainly focused their attention on prevention, answer to and cure against hydrocarbon spills and other potentially dangerous substances - the so-called Hazardous and Noxious Substances (HNS)- in case of accidental sea pollution.

Given the complexity of decontamination activities, the fight against sea pollution requires a well-defined system of response and an efficient ruling structure that makes a good use of the resources. Therefore, it is necessary to focus on the organization of response mechanisms and establish a program that can confront any accidental sea pollution event successfully. The increasing marine transport of dangerous goods - especially hydrocarbon - that pass near the Canary coasts and the current interest of oil prospections close to Fuerteventura and Lanzarote, make the Canary Islands a threatened setting with serious consequences for the coast.

The research developed in this project is mainly dedicated to the upgrade of the Specific Plan of Contingencies due to Accidental Sea Pollution in the Canary Islands (PECMAR) because of the new ruling in what has to do with marine pollution and the studies that aim to find oil in Canary waters or other surrounding areas whose possible oil spills can affect the Canary Islands. The risk of hydrocarbon contamination might be caused by accidents during oil prospections or by oil tankers

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transporting crude oil. Whatever the origin of pollution is, there is a risk for certain coastal areas to be affected by hydrocarbon spills which could deal to a great environmental and economic impact. These economic consequences can be directly originated due to the cost of oil spill treatment. Indirectly, hydrocarbon spills can affect tourism and this echoes on economy too.

2. Methodology.

Through Oil Spill Model and Response System (OILMAP) and the Island Response and Operations System against Ocean Pollutants, in Spanish Sistema Insular de Respuesta y Operaciones Ante Contaminantes Oceánicos (SIROCO) it is possible to reproduce and analyse the behaviour and evolution of pollutant spills in the sea. This complete system will be used operationally in emergency events and in the response plan to confront any pollutant spill. It is based on the direct access and implementation of a series of models to help in decision making to confront a spill. It also means a useful tool in the design, process and evaluation of the most suitable contingence performing plan with the objective of minimizing the different effects of spills and managing the affected ecosystems.

A series of discussion points on the hypothetical impact of oil prospections authorized by the Spanish government have been selected as well as three specific locations of strategical probings in the offshore regions of oil interest for Morocco. A double stochastic study will be done considering two seasonal periods: summer (May-October) with a slight intensification of trade winds and winter (November-April) with a bigger influence of winds from different directions. In the same way, a determining study will be done.

The methodological study can be divided into different stages. At first, the focus was on those basic phenomena that take part in the evolution of the stain track and the aging process of the pollutant. After that, SIROCO made a study of the possible impact of different amounts and types of hydrocarbon mixtures on different coasts under the effect of diverse weather conditions existing during the spill and after it. This study also focused on the possible effects in the Specially Sensitive Marine Area.

With the use of different simulation models, we can determine the ways that different amounts and types of hydrocarbons spilt under different weather conditions may follow.

2.1. The OILMAP system.

OILMAP (OIL SPILL MODELLING), developed by Applied Science Associates (ASA), incorporates a series of computing models that allow us to manage emergency plans through the real time monitoring of oceanic and weather conditions. This helps to predict the way and aging process of any hydrocarbon spill parting from simulations in different zones of potential risk.

The basic modules available in OILMAP are: Determining Model of Drift and Aging Processes, Stochastic Mode (based on probability valuing the risk of impact in contingency plans) and Subsurface Transport Model. It also incorporates a backtrack model that allows to predict the origin of an oil stink having information about its current position and its drift.

Model of Drift and Aging.

- It predicts the way for instant and continuous spills.
- It includes algorithms for the different aging stages of hydrocarbon and interactions with different types of coast.
- Animation of the hydrocarbon movement identifying the impact on the coast.
- Representation of the aging evolution of the HC in time and visualization of the resources impacted by the spill, which are represented in the SIG.

Stochastic Mode.

- It determines the probability of different ways that an oil spill can take along one month, one season or in a year.
- It shows the percentages of probability to find hydrocarbon in the surface or in the coast close to the spill zone. It also gives the spill position in each time.

Receptor Mode (oil vulnerability analysis).

1. It determines the vulnerability of a particular area to be affected by an oil spill, caused by a risky site or by boat traffic.
2. It reflects the possible source of the spill when this is observed from a specific site.

Subsurface Transport Model,

1. It predicts the oil transport in the water column as well as its incorporation and dissolution.

The PETROBRAS report (2009) compiles a detailed study of the equations used in OILMAP, which are explained in the following paragraphs. Through the hydrodynamic model, the drift model predicts the hydrocarbon transport and its degradation process parting from instant or continuous spills. Moreover, it predicts the temporal variation of the covered area and the stain thickness, the amount of hydrocarbon on the sea surface and the water column, the amount of evaporated oil as well as the amount that reaches the coast or stays outside of the domain.

The algorithm used in OILMAP conceives the stain as a group of lagrangian particles, each of them with a known mass. The position vector X ? of a certain particle in a certain moment t is determined through the following equation:

$$\overrightarrow{X}_t = \overrightarrow{X}_{t+\Delta t} + \Delta t \cdot \overrightarrow{U}_{oil} \tag{1}$$

where:

- Δt: time increase (s)
- $\overrightarrow{X}_{t+\Delta t}$: position in $t + \Delta t$
- $\overrightarrow{U}_{oil}$: stain velocity (m/s)

The advective velocity of the particle ($\overrightarrow{U}_{oil}$) comes defined by:

$$\overrightarrow{U}_{oil} = \overrightarrow{U}_w + \overrightarrow{U}_t + \overrightarrow{U}_r + \alpha\overrightarrow{U}_e + \beta\overrightarrow{U}_p \quad (2)$$

where:

- $\overrightarrow{U}_w$: component of the velocity due to wind and waves (m/s)
- $\overrightarrow{U}_t$: component of the velocity due to sea current (m/s)
- $\overrightarrow{U}_r$: component of velocity due to residual flow (m/s)
- $\overrightarrow{U}_e$: component of velocity due to Ekman flow (m/s)
- $\overrightarrow{U}_p$: component due to blowout (m/s)
- α: 0 for surface spill; 1 for subsurface spill
- β: 0 for spill without a blowout; 1 for spill with blowout

The component of advective velocity due to sea currents ($\overrightarrow{U}_t$) and to the residual flow ($\overrightarrow{U}_r$) are specific of the hydrodynamic model. The components of drifting velocity due to wind u_{wc} (East-West) y v_{wc} (North-South) are taken from the following expressions:

$$u_{wc} = C_1 u_w \quad (3)$$

$$v_{wc} = C_1 v_w \quad (4)$$

where:

- u_w: components East-West of wind velocity (m/s)
- v_w: components North-South of wind velocity (m/s)
- C_1: drifting factor (%) based on observations (1.0-4.5%). Values of 3-3.5% are related to moderate winds in open sea. Lower values are used in protected coast areas (estuaries, bays, etc). The default value is 3,5%.

The components of drifting velocity due to wind are formulated using the expression:

$$u_{wd} = u_{wc}\cos\theta + v_{wc}\sin\theta \quad (5)$$

$$v_{wd} = u_{wc}\sin\theta + v_{wc}\cos\theta \quad (6)$$

where:

- u_{wd}: components East-West of drifting velocity due to wind (m/s)
- v_{wd}: component North-South of drifting velocity due to wind (m/s)
- θ: drifting angle (°)

Using the filing "random walk" it is possible to simulate the horizontal dispersion processes that take place in a movement scale lower to the current camp resolution scale, which is given by the hydrodynamic model. The components of stain dispersion velocity (u_{dd} y v_{dd}) are defined by (BEAR & VERRUIJT, 1987):

$$u_{dd} = \gamma\sqrt{\frac{6D_x}{\Delta t}} \quad (7)$$

$$v_{dd} = \gamma\sqrt{\frac{6D_y}{\Delta t}} \quad (8)$$

where:

- D_x: coefficient of horizontal dispersion in the East-West wind (m^2/s)
- D_y: coefficient of horizontal dispersion in the North-South wind (m^2/s)
- Δt: time increase
- γ: random number between -1 y 1

The stain dispersion process is represented by the formulation of Mackay et al. (1980a,b, 1982) and an analysis of the algorithm effectivity. With the objective of minimizing the dependence on the number of particles used, Kolluru (1992) implemented a model to normalize the solution with different numbers of surface particles. The rate of variation in the surface area (m^2/s) of one particle comes like this:

$$\tilde{A}_{tk} = \frac{dA_{tk}}{dt} = K_1 A_{tk}^{1/3}\left(\frac{V_m}{A_{tk}}\right)^{4/3}\left(\frac{R_s}{R_e}\right)^{4/3} \quad (9)$$

where:

- A_{tk}: stain surface area (m2)
- K_1: rate of constant dispersion (s^{-1})
- V_m: volume of a particle (m^3)
- R_s: radio of a particle (m)
- R_e: effective radio of the stain surface (m)

The evaporation process is based on the analytic equation defined according to evaporation exposure (Mackay et al., 1980b, 1982, 1984). The model uses data from the curves of oil distillation to estimate the necessary settings in this analytic equation.

The evaporated fraction F_v comes like this:

$$F_v = \frac{ln\left[1 + B(T_G/T)\theta\exp(A - BT_0/T\right]}{\left[T/BT_G\right]} \quad (10)$$

where:

- T_0: initial boiling point (K)
- T_G: curve gradient of modified distillation

- T: ambient temperature (K)
- A, B: dimensionless constants
- θ: evaporation exposition

Data of the oil distillation curve (T_0, T_G, A, B) can be obtained from the data base “Environment Canada’s Oil Catalog” or through experimental procedures. Dragging processes are modelled using Devigne-Sweeney’s formulation (1988), which represent the crude injection rate in the water column by little oil drops. The dragging coefficient is determined by the oil viscosity according to Delvigne-Hulsen (1994). The following relation determines the oil dragging rate depending on the size of particles:

$$Q_d = C^* D_d^{0.57} S F d^{0.7} \Delta d \tag{11}$$

where:

- C^*: dragging empirical constant that depends on the type of hydrocarbon and time
- D_d: energy dissipated by the waves per unit of surface area (J/m^2)
- S: fraction of sea surface covered by crude
- F: fraction of sea surface affected by waves
- d: diameter of oil particles (m)
- Δd: diameter range of oil particles (m)

The oil emulsion process is based on a specific formulation given by Mackay et al (1980a, 1982), depending on evaporation loss and alterations in the proportions of water in the mixture. This process also depends on the oil features and the sea state. The emulsion method proposed by Mackay explains the water rate incorporated to the crude according to:

$$\tilde{F}_{wc} = \frac{dF_{wc}}{dt} = C_1 U_w^2 \left(1 - \frac{F_{wc}}{C_2}\right) \tag{12}$$

where:

- U_w: wind velocity (m/s)
- C_1: chemical constant ($2x10^{-6}$ for emulsified oil; 0 for the rest)
- C_2: constant that controls the maximum amount of water (0.7 for heavy or crude fuels)
- F_{wc}: maximum fraction of water in oil (s^{-1})

The viscosity of emulsified oil (μ (cP)) is given by:

$$\mu = \mu_0 exp\left(\frac{2,5F_{wc}}{1 - C_0 F_{wc}}\right) \tag{13}$$

where:

- μ_0: itinial viscosity of oil (cP)
- F_{wc}: maximum fraction of water in oil
- C_0: emulsification constant (~0,65)

3. Results and Analisys.

3.1. Exploration Region CANARIAS-6 (OILMAP).

3.1.1. Continuous Spill of 960m^3 (Light Arabian). Stochastic Analysis.

Table 1 indicates the parameters to enter OILMAP model to the exploration region CANARIAS-6, in fix average Ocean and weather conditions in case of a continuous spill of 960m^3 of Medium Crude during 96 hours.

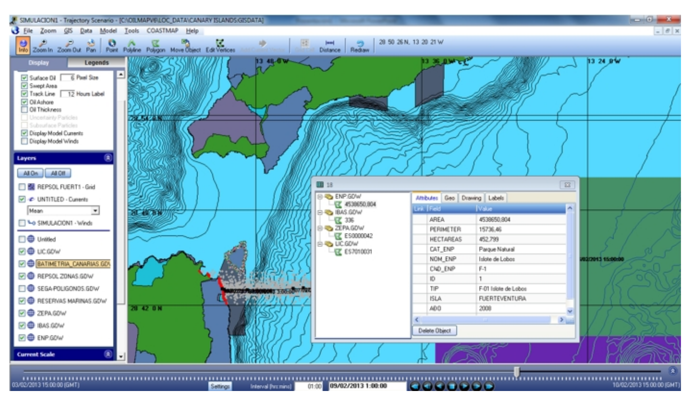
Table 1: Model inputs and parameters OILMAP (CANARIAS-6). Oil spill 960 m^3 Arabian Light. Software OILMAP.

Spill Point Coordinates	**Longitude**	**Latitude**
	13º 25`00” W	28º 45`00” N
Crude type	Arabian Light	
Wind Velocity	10 m/s	
Angle	90º	
Current Velocity	0,2 m/s	
Current direction	SW	
Sea Temperature	18ºC	
Flow rate	10.000 L/h	
Spill duration	96 hours	
Simulation time	7 days	

Source: Authors.

Figure 1 shows the specifications of the Geographic Information System, which has been used in OILMAP, to demonstrate data that confirms Lobos Island as a risky area to be affected by an oil spill.

Figure 1: GIS data of the region affected by the slick (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.

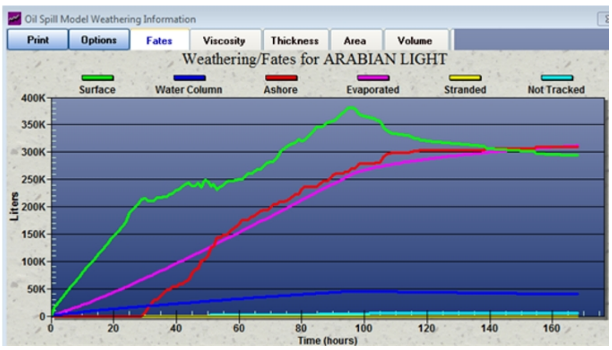


Source: Authors.

A serious disease is observed in the Natural Park of Lobos Island. This region shelters more than 130 vegetable spieces and several species of birds like the gull, the great bustard – in specific moments of the year – and the gray heron. The ocean floors mean a marine reserve with a great ecological richness.

Figure 2 shows a variation in time in the hydrocarbon volume, which stays on the sea surface. It is also observed the evaporated oil, the oil that reached the coast and the one inside the water column.

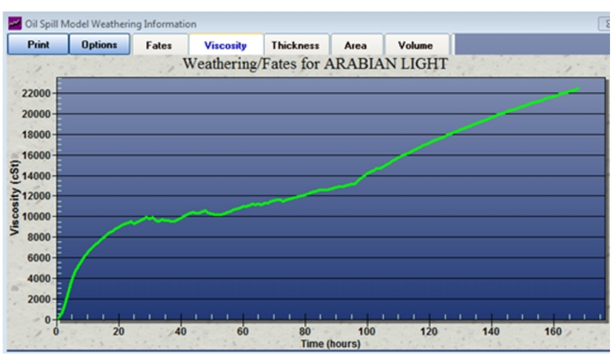
Figure 2: Variation of the quantity of evaporated hydrocarbon depending on time, remaining at sea and impacting the coast (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 3 shows the variation in time of the hydrocarbon mixture viscosity.

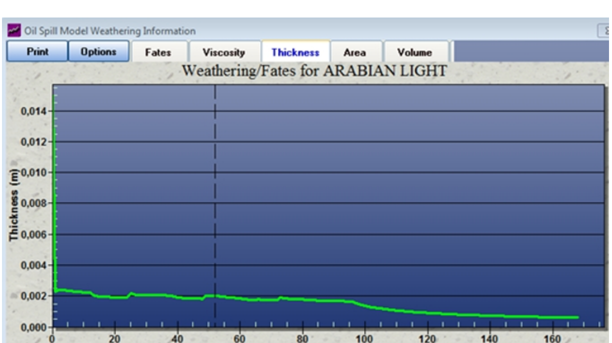
Figure 3: Variation in time of the hydrocarbon mixture viscosity (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

The variation of thickness in time is shown in Figure 4.

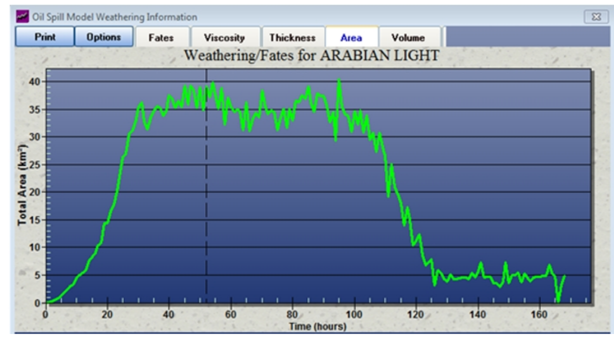
Figure 4: Variation of surface oil thickness (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 5 shows the variation of the total area of the spill according to time.

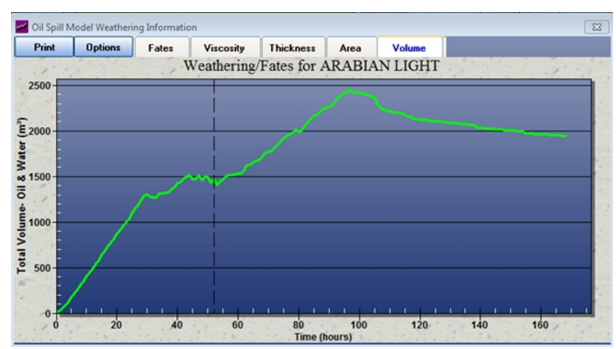
Figure 5: Variation of the total area of the spill according to time (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 6 shows the variation in the volume (hydrocarbon - water) in each moment.

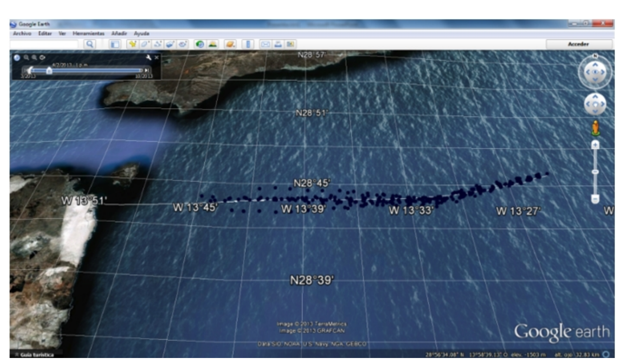
Figure 6: Variation in the volume (hydrocarbon - water) (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 7 shows the track followed in the first hours of the spill evolution in Google Earth. ,

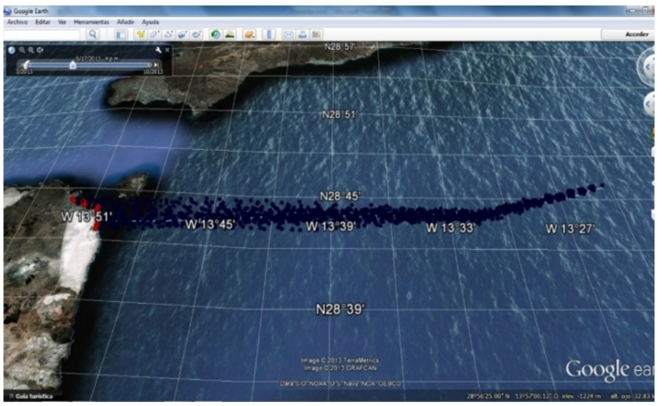
Figure 7: Oil spill track followed in the first hours (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 8 shows the final track of the spill, which has been exported to Google Earth. It indicates the coast areas initially affected by hydrocarbon.

Figure 8: Final track of the spill, which exported to Google Earth (CANARIAS-6) (Zoom In). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

After analyzing the simulations, it is demonstrated that the majority of the coast areas affected by the oil spill are located from 28º 42,3‘N to 28º 43,8‘N and from 13º 50,2‘W to 13º 53,1‘W. Figures are cited in the text as follows: See Fig. 1. The title of the figure will be indicated at the top of the figure and they will be numbered sequentially.

3.1.2. Continuous Spill of 960m^3 (Light Arabian). Deterministic Analysis.

Table 2 indicates the parameters to enter OILMAP model to the exploration region CANARIAS-6, analysing a hypothetical continuous spill of 960m? (Light Arabian) during 96 hours deterministically. This is interpreted according to the ocean and weather conditions existing along the storm that occurred in the Canary Islands in December 2013.

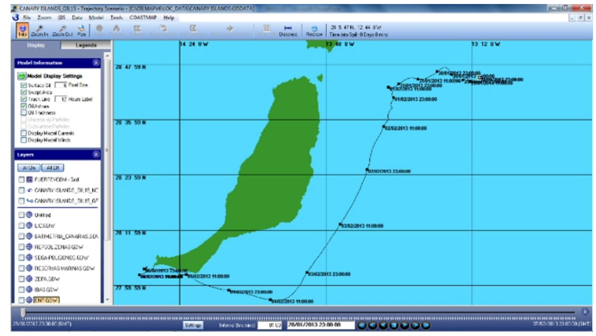
Table 2: Model inputs and parameters OILMAP (CANARIAS-6). Oil spill 960 m^3 Arabian Light. Software OILMAP.

Spill Point Coordinates	**Longitude**	**Latitude**
	13º 10` 00" W	28º 45`00" N
Crude type	Arabian Light	
Wind Velocity	GFS (NCEP)	
Current Velocity	GLOBAL NCOM (NAVY)	
Sea Temperature	18ºC	
Flow rate	10.000 L/h	
Spill duration	96 hours	
Simulation time	10 days	

Source: Authors.

Figure 9 shows a foresight of the spill track until the moment it impacts into the coast of Fuerteventura.

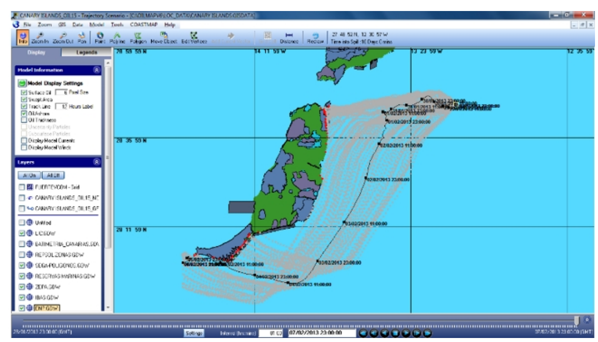
Figure 9: Forecasting Trajectory (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 10 represents the position of the oil spill after 250 hours

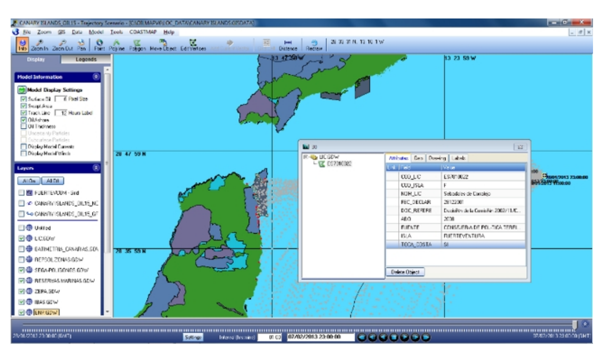
Figure 10: Position of the spill after 250 hours (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

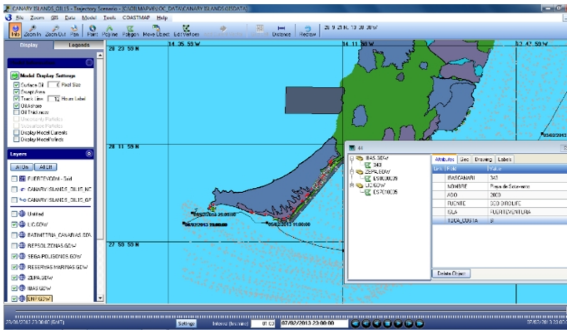
The following figures show specifications of the Geographic Information System in the surroundings of the risky regions to be affected by an oil spill. The main sensitive areas are the Natural Park of Lobos Island, the ZEPA Corralejo Dunes - Lobos Island, LIC Sebadales of Corralejo (Figure 11), Natural Park of Corralejo, Jable of Corralejo, Seo Birf Life Sotavento Beach (Figure 12) and ZEPA Jandía.

Figure 11: GIS data of the region affected by the slick o (LIC Sebadales de Corralejo) (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

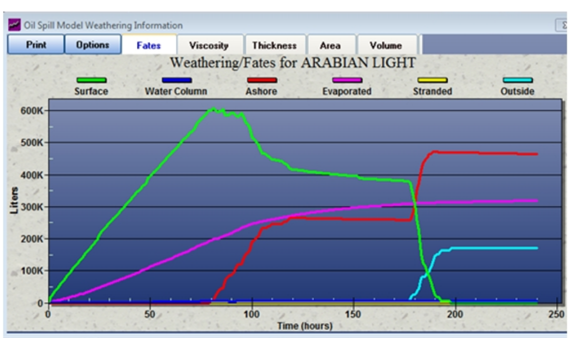
Figure 12: GIS data of the region affected by the slick (Seo BirdLife Beach of Sotavento) (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 13 shows the variation in time of the volume of hydrocarbon that stays on the sea surface, the evaporated hydrocarbon, the one that reached the coast and the oil inside the water column.

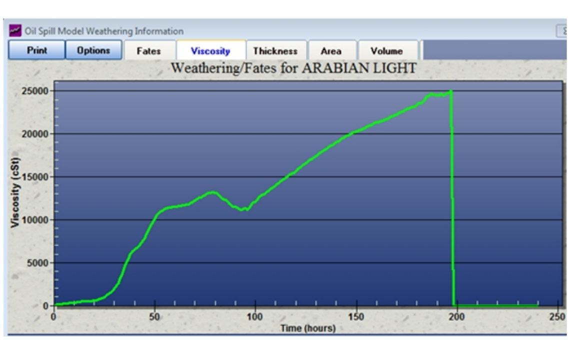
Figure 13: Variation of the quantity of evaporated hydrocarbon depending on time, remaining at sea and impacting the coast (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 14 explains the time variation in the viscosity of the remnant hydrocarbon mixture:

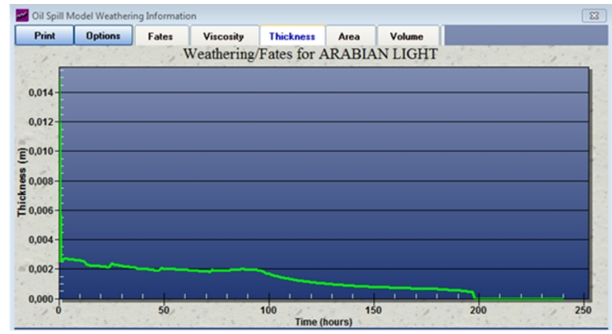
Figure 14: Variation in time of the hydrocarbon mixture viscosity (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

The time variation in the oil thickness is shown in Figure 15.

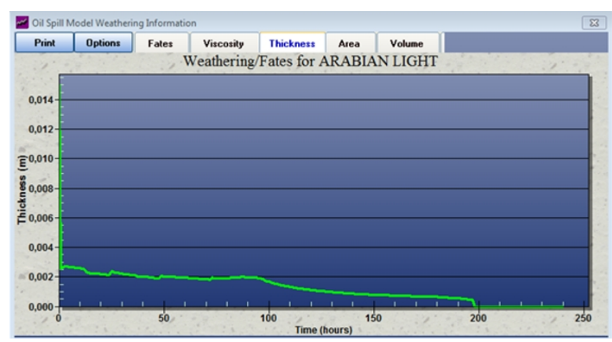
Figure 15: Variation of surface oil thickness (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 16 shows the variation in the total area of the spill according to time.

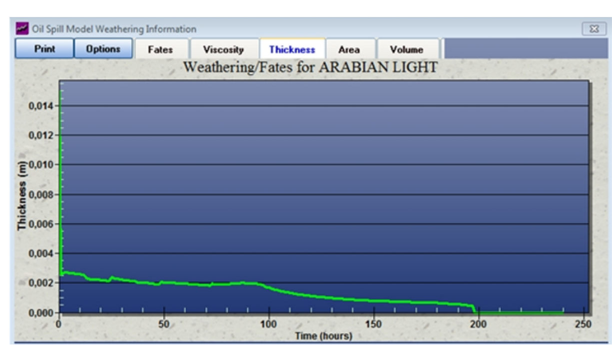
Figure 16: Variation of the total area of the spill according to time (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 17 demonstrates the volumen variation (hydrocarbon - water) in each moment:

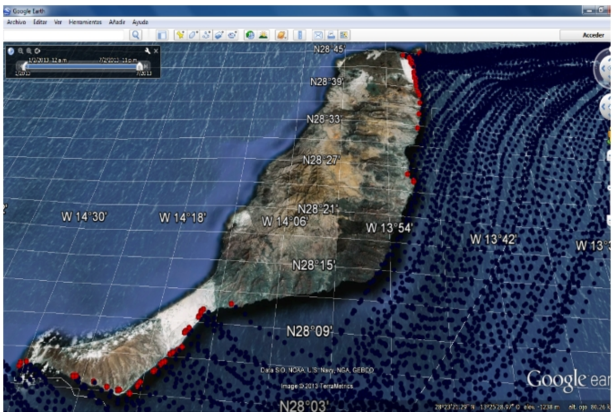
Figure 17: Variation in the volume (hydrocarbon - water) (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



Source: Authors.

Figure 18 explains the final track of the spill, which has been exported to Google Earth, and indicates the coast areas initially affected by the hydrocarbon.

Figure 18: Final path of the spill and the coastal areas initially affected by the Hydrocarbons (CANARIAS-6). Oil spill 960m^3 Arabian Light. Software OILMAP.



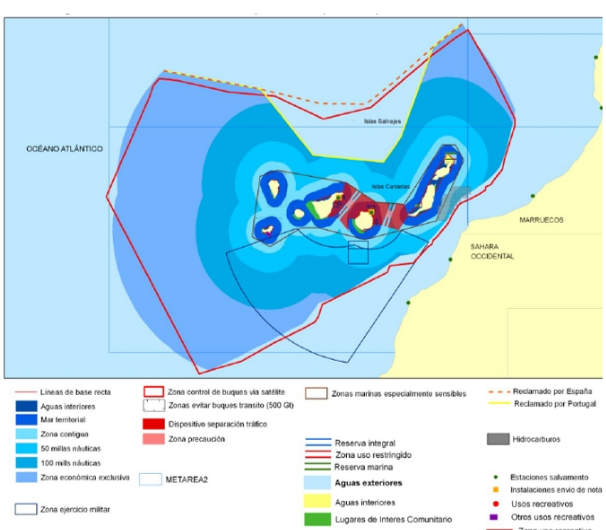
Source: Authors.

After analysing the simulations, two coast regions can be delimited. These are the ones mostly affected by the oil spill: North-East region with the coordinates 28º 45‘N a 28º 25‘N and 13º 50,8‘W 51,2‘W and the South-East region with the coordinates 28º 03‘N a 28º 10,8‘N and 14º 30‘W a 14º 15‘W.

Conslusions.

The evaluation of oil spill consequences must be done from a global perspective, considering the inter-relation existing between different environmental factors and the Regions of Marine Interest of the Canary Islands (Figure 19).

Figure 19: Regions of Marine Interest of the Canary Islands.



Source: Propuesta De Ordenación de las Aguas Jurisdiccionales Españolas. Proyecto MEC (SEJ2007-66487 / GEOG), (2007).

When oil crude and other hydrocarbon mixtures are released to the sea, they are affected by the action of different weather and marine factors. Due to this phenomenon, they change their state or environment. They are driven by the wind and the water currents and therefore, spread and dispersed along the sea surface, the seabed and even the atmosphere. The increase of their range of action, combined with different aging processes, makes it difficult for the physical and chemical characteristics of the environment to stay and endure in order to develop a normal biotic.

Table 3 shows some effects of the crude on diverse populations of living beings, both short and long terms, as well as their recovery possibilities. (BERGUEIRO, J.R. et al., 2001).

Table 3: Effects of hydrocarbon pollution over some living species.

Population	Sensitivity	Short-term Effects	Long-term Effects	Recovery
Algae	Low	Coating and burning when in contact with the pollutant	Little	Good
Flora of estuaries and marshes	Changeable, according to the degree of vegetation development and the season	- Asphyxiation of covered parts - Impact of the intervention team over the estuaries	Little	-Relatively fast (2-3 years) if there is water renovation and the necessary nutrient input -Slow if nothing is done
Intertidal zone Molluscs	Generally High	Asphyxiation and poisoning	- Accumulation in the filter animals -It makes the species useless for consumption -Reproduction decrease	- Possibility of recovery through water cleaning if the time of contact has been short
Rock wildlife	Generally high	Asphyxiation and poisoning	- Depending on the time of contact -Lower impact in areas hit by water	-It depends on the duration of the impact. Again, water cleaning is a possibility.
Fish	- Short for the adults -High for larvae and young species	-Asphyxiation by hydrocarbon covering and the effects of the surfactant components in the gills -Abandonment of the area	-Injuries in seabed buried fish even at low contamination level	-Afterwards depending on the recovery of other species
Birds	Changeable in diving birds	- Feather covering -Poisoning by ingestion -Destruction of nets and eggs	-Evacuation of the polluted areas	-It depends on the recovery of other species

Source: Authors.

Oil spills not only affect human, animal and plant health. They also have effects on economy: agriculture, animal breeding, fishing, fish farms, transformation industries and commerce, etc. More indirect damage could be added in what has to do with water supply, transport, port activities and even tourism or leisure life.

Oil spills affect water supply in the Canary Islands when they reach the catchment areas, both from aquifers and desalination plants. Leisure life can be affected when the spills reach beaches, sport springs and commerce ports, tourism, etc. All of them are essential today, particularly in the Canary Islands.

The environmental damage of an oil spill may vary depending on the place where it takes place, in shallow waters where the ecosystems are particularly sensitive or in open abyssal regions. Aging progression decomposes oil in microscopic particles that are degraded through natural processes. In the recent Deepwater Horizon spill, approximately 16% of the spill was eliminated through natural processes. Despite the fact that few studies exist about the impact of oil spills over the complex ecosystems in deep waters, recent investigations about the consequences of the Deepwater platform spill confirm that a big amount of oil tends to be located on the surface of the seabed. This causes the death of abyssal wildlife, burying submerged habitats of a great ecological value. Nowadays, the long-term impact over ecosystems is unknown (KRUPNICK, 2011). The effects of an oil spill in the marine environment depend on diverse factors. In Table 4, we can see a scheme of the potential impact of a spill on the sea environment depending on their main source. The different impacts are classified as Low (L), Medium (M), High (H), Unknown (ND) or Without Impact (- -).

Table 4: Environmental impact of humans over different oil activities.

	Fish and invertebrate displacemen	*Fish and invertebrate mortality*	*Seabird and marine mammal mortality*	*Contamination to fish and invertebrate populations*	*Shoreline contamination*	*Habitat loss or alteration*	*Surface water quality*	*Groundwater quality*	*Air quality*	*Mortality*	*Morbidity*
OIL EXTRACTION (DEEPWATER)	ND	ND	L	ND	ND	ND	M	--	M	L	M
offshore platform	ND	ND	ND	ND	ND	ND	M	--	--	L	M
OIL EXTRACTION (SHALLOW WATERS)	M	H	M	H	H	M	H	--	H	L	L
offshore platform	M	H	M	H	H	H	H	M	H	L	L
TRANSPORTATION	H	H	H	H	H	H	H	M	--	L	L
pipeline spill	H	H	H	H	H	H	H	M	--	L	L
tanker spill	H	H	H	H	H	H	H	--	--	L	L
Coastal facility spills	H	H	H	H	H	H	H	--	--	--	--

Source: Authors according to Krupnick, (2011).

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