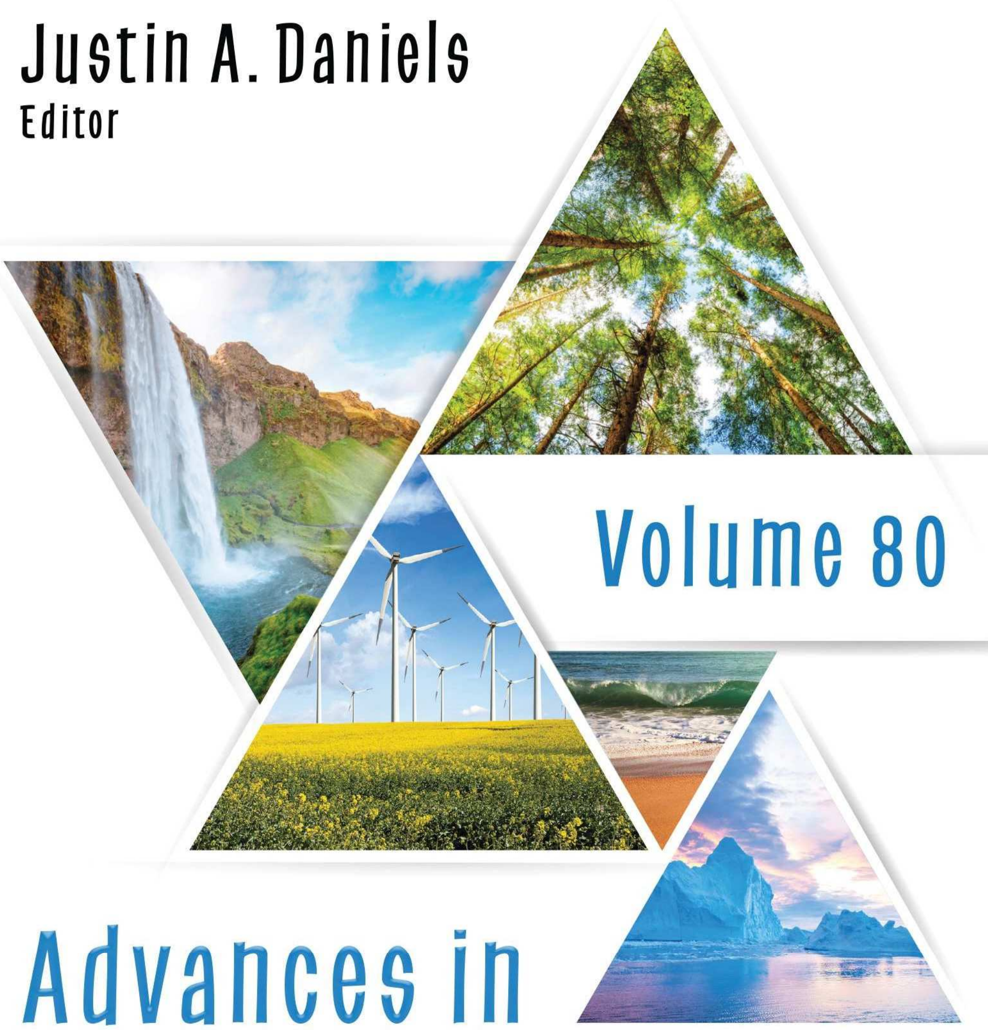
Justin A. Daniels
Editor



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Chapter 4

ENVIRONMENTAL IMPACTS OF OIL SPILLS AND RESPONSE TECHNOLOGIES

Abdellatif Soussi[1,×], Chiara Bersani[1,2]
and Roberto Sacile[2]
[1]Italian Centre of Excellence on Logistics, Transport and Infrastructures (CIELI), University of Genova, Genova, Italy
[2]Department of Informatics, Bioengineering, Robotics, and Systems Engineering, University of Genova, Italy

ABSTRACT

Oil spill accidents are among the most environmentally damaging disasters in the world because of their serious consequences which can be identified in several areas such as the marine biological and physical environment, human health and society, economy, and politics. The environmental impacts of the oil spill in the marine environment can be directed or indirected as well as acute effects ranging from a few days to several years and chronic long-term effects. For this reason, several intervention methods are considered during oil spills in order to limit the deleterious damages of the incident and thus to protect the environment.

[×] Corresponding Author's E-mail: abdellatifsoussi90@gmail.com.

These methods can be physical/mechanical, chemical, or biological. However, the choice of a response method is a considerable challenge both in environmental and economic viewpoints. Many variables can influence the environmental effects of a spill and the choice of response practices, such as location, weather conditions, spill rate, and type of oil. Within this context, the main purpose of this work is to highlight oil spills through a detailed review of the past oil spill accidents, analysing physical and chemical processes in water due to the released materials and the main environmental impacts as well as the countermeasures and clean up techniques.

Keywords: maritime accident, oil spill, environmental impact, response methods

INTRODUCTION

The oil spill is one of the most dangerous sources of pollution that threaten maritime safety because of its serious consequences as demonstrated by past and recent disasters, such as the case of the Exxon Valdez oil spill in 1989 which released around 55,000 barrels gallons of crude oil (Gill et al., 2012), and the Deep Horizon accident in 2010 (4.26 million bbl) (French-McCay et al., 2018). In the Mediterranean Sea, as an example, more than 100 million gallons of crude oil are spilled each year (Hosein et al., 2019; Cláudio et al., 2014), with 52% of total oil spills coming from maritime transport (Albakjaji, 2011).

Generally, the black products (fuel oil, tars) are the most polluting products, while white petroleum products (WPP) (i.e., diesel, gasoline, kerosene, naphtha) are rather more dangerous because of their flammability, but less polluting because of their volatility (Speight, 2020; Major and Wang, 2012). In the case of an oil spill in the marine environment, it is subjected to the effects of the environment that generates its dispersion in the marine environment and, simultaneously, it modifies its physical and chemical characteristics, which is called "weathering" of the oil (Soussi et al., 2019; Mishra and Kumar, 2015). The behavior of oil drift at sea is the result of a set of interactions that occur between the spilled product and the conditions of the external environment (NRC, 2003). When the oil is discharged at sea, it undergoes a large number of transformation processes: drift and spreading, evaporation, dissolution, dispersion, emulsification, photooxidation, biodegradation, sedimentation, spillage, stranding, and interaction with sea ice (Soussi et al., 2020; Spaulding, 2017). While some processes are currently well understood, such as spreading and evaporation, others remain poorly understood (photo-oxidation and biodegradation) (Liu et al., 2012; Yim et al., 2011).

There are multiple environmental effects of the oil spill in the marine environment (Soussi et al., 2020). They lead to serious impacts on ecosystems where they cause the degradation of marine flora and fauna (Witchaya et al., 2017; Al-Majed et al., 2012; A.Vega et al., 2009; Ventikos et al., 2004). As most oil floats on the surface of the water, it can cause considerable damage to seabirds and marine animals (Barron, 2012), and other land creatures and animals are injured if the oil arrives on land (Brody et al., 2012). In addition to the negative impacts for the economy and the population near the contaminated shoreline which often live on tourism and fishing activities (Etkin et al., 2017; Daly et al., 2016). The effects of oil spills on the environment depend on several variables such as location, duration of the spill, surrounding marine and weather conditions, quantity, rate of the spill, and the type of oil (Jafarinejad, 2017).

Given the severity of the impacts that an oil spill can produce on the environment, it is important to be able to prioritize actions to improve spill response and thus better protect the environment (Dave and Ghaly, 2011). Oil spill treatment methods can be classified as physical/mechanical (i.e., booms, skimmers), chemical (i.e., dispersants, sorbent materials), or biological (i.e., biodegradation and bioremediation) (Singh et al., 2020; ITOPF, 2012). However, this choice may be conditioned by a multitude of factors that have a particular impact on the response and the extent of the impacts of the spill, including the sensitivity of the environment and organisms, environmental conditions, and the type of oil product spilled (Gong et al., 2014; Fingas, 2013; Lessard and Demarco, 2000). Many other factors must also be considered depending on the features of the spill and its location. In this regard, the oil spill treatment method to be used has to satisfy an optimization problem whose objective minimizes both the environmental impact and the cost of the operation (Doshi et al., 2018; Prendergast and Gschwend, 2014).

HISTORICAL SPILL ACCIDENTS

Oil pollution related to maritime transport activities in the Mediterranean Sea has two main origins (operational pollution, accidental pollution).

- Accidental Pollution may result in the loss of cargo or fuels as a result of grounding, collision and minor accidents occurring on board the ship, thus accidental pollution is random;
- Operational pollution results from the discharge of ship-generated wastes such as garbage, sewage, dirty bilge water, and tank cleaning water as well as engine exhaust and tank ventilation emissions.

Accidental pollution, illustrated by massive oil pollution, is however less important in quantity than operational pollution. Oil spills caused by accidents account for at least 30% of this pollution, compared with 70% for operational pollution (Albakjaji, 2011).

Accidental spills attract the attention of the public, the media and politicians, while operational pollution does not have this standing out. This latter is due to a lack of information on its frequency and its harmful effects on the environment marine. In addition, accidental pollution appears to be more irritating than any other categories of marine oil pollution, probably because of their concentrated nature.

The major accidents oil spill occurred in the world can be summarized in the following table:

Table 1. The major accidents oil spill occurred in the world according to chronological order

Spill/Vessel	Dates	Description
Torrey Canyon	18 March 1962	Grounding of a tanker in charge near the English Cornish coast: the first massive oil spill (80,000 tons) in the history of shipping, and the first oil spill affecting two countries (the United Kingdom and France) (Nanda, 1967).
Amoco Cadiz	16 March 1978	Grounding of a tanker in charge on the Breton coast (the largest spill at the coast (210,000 tons of crude oil in 15 days) of the history of maritime transport) (Boucher, 1980).
Atlantic Empress	19 July 1979	Collision and fire of two tankers in charge of crude oil (276,000 tons) off Trinidad: a larger oil spill (207,000 tons of crude oil, partly burned) (Horn and Neal, 2005).
Tanio	7 March 1980	Breakdown of a tanker in charge (26,000 tons of crude oil), causing a small spill (9,000 tons), but in an area affected two years earlier by an exceptional spill (Amoco Cadiz) with a relief of a part of submerged wreck (Berne and Bodennec, 1984).
Exxon Valdez	24 March 1989	Grounding of a tanker in charge (180,000 tons of crude oil) in Alaska, causing à medium-sized spill (40,000 tons) (Peterson et al., 2003).
Kharg-5	19 December 1989	Explosion of an Iranian oil tanker carrying 284,000 tons of crude oil and drifting along the Moroccan coast, between Safi and Larache, leaving slicks of water hydrocarbons at a rate of 200 tons per hour (Darmame, 1992).
Haven	11 April 1991	Fire and explosion of a tanker in charge (144,000 tons of crude oil), at anchor in front of Genoa (Bolognesi et al., 2006).
Aegean Sea	3 December 1992	Grounding of a tanker in charge at the entrance of the Port of Corunna, Spain: an average spill (80,000 tons of crude oil, combustion of the part), but in a zone of very strong fisheries exploitation (Solé et al., 1996).
Braer	5 January 1993	Stranding of a tanker in charge on a rocky coast of the Shetland Islands: on average spill (85,000 tons of crude oil) in exceptionally bad weather conditions (Kingston et al., 1995).
Sea Empress	15 February 1996	Grounding of a tanker in charge (130,000 tons of crude oil) at the entrance to Milford Haven Bay, Wales: an average spill (72,000 tons), subject of a dispersant treatment of a dimension never before seen (Lyons et al., 1999).
Katja	7 August 1997	The pollution of the oil tanker Katja in the Port of Le Havre illustrates an essential fact: an accidental spill of hydrocarbons, altogether modest, compared to major accidents. The quantity transported: 80,000 tons, the quantity dumped 187m^3. The factor leading to the accident is the damage (Cabioc'h and Cariou, 2005).

Table 2. (Continued)

Spill/Vessel	Dates	Description
Erika	12 December 1999	Breakdown of a tanker in charge (31,000 tons of heavy fuel oil) off Brittany: the first large spill of heavy fuel oil (20,000 tons) and a relief of submerged wreck (11,000 tons) (Bocquené et al., 2004).
Prestige	13 November 2002	Breakdown of a tanker in charge (77,000 tons of heavy fuel oil) off Galicia: a heavy fuel oil spill (estimated at 64,000 tons), the European record for the length of affected coastline (more than 3,000km) and unprecedented wreck relief (13,000 tons recoveree more than 3,800 m of background) (Albaigés et al., 2006).

According to ITOPF data (ITOPF, 2020), oil spills had a decreasing trend in the last 50 years, when we can observe that the average number of spills per year has decreased by more than 90% reaching a minimum of 6 compared to the 1970s which was about 79 (Figure 1). The following map made by ITOPF shows the geographical locations of spill accidents during the period 1970 and 2019 (ITOPF, 2020).

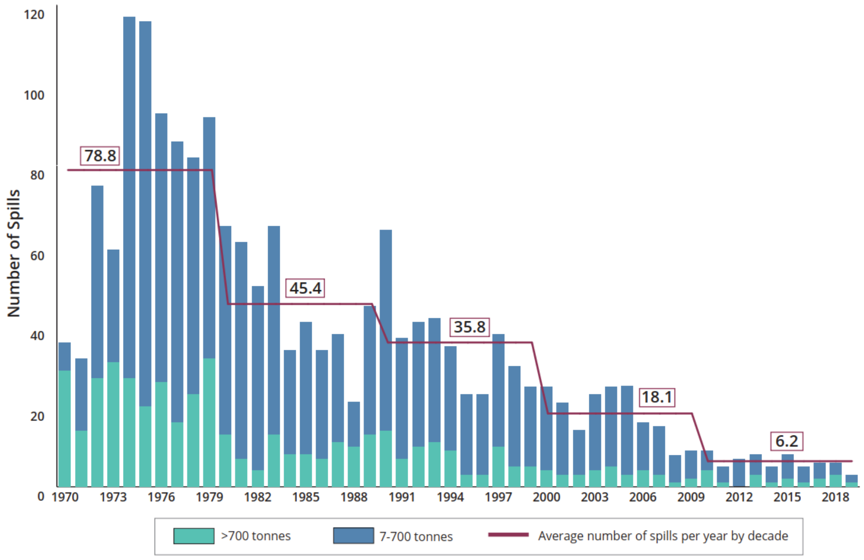
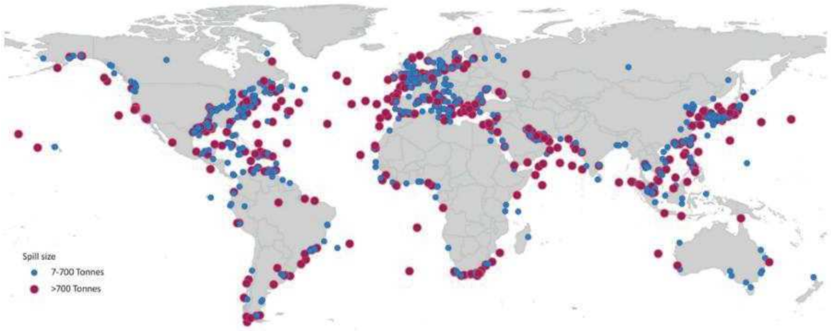


Figure 1. Number of spills according to ITOPF data from 1970 – 2019.



Source ITOPF, 2020.

Figure 2. Geographical locations of spill accidents during the period 1970 and 2019 according et ITOPF database.

HYDROCARBON WEATHERING PROCESS

The behavior of hydrocarbons at sea depends strongly on the nature of the spilled products, but it must also be accounted the area of the spill (coastal zone, estuary, offshore) and the weather-ocean conditions (tide, currents, wind, agitation of the sea, sunshine).

A petroleum product is subjected to the effects of the environment which causes the dispersion in the marine environment and, at the same time, modifies their physical state and their chemical characteristics. This process is called the weathering of oil (Yim et al., 2011). No accident is precisely the same; the behavior of hydrocarbons released at sea is the result of a set of interactions that exist between the spilled product and the sea conditions and the prevailing weather (Zhang et al., 2015).

The crude oils are complex mixture and combination of hydrocarbons: that’s why their consistency may change from a volatile liquid to viscous semi-solid product. The refined products represent different distillation fractions of crude oils in ascending order by their density: gasoline, kerosene, fuels, lubricating oils, residual fuels, bitumen. Also, a petroleum product that belongs to hydrocarbon product is characterized by chemical composition and its physical properties (Hollebone, 2011; Wang et al., 1999). In general, there are two main categories of hydrocarbons; the aliphatic hydrocarbons which are composed of the linear open chain (n-alkanes), or cyclical (Naphthenes) with five or six carbon atoms (cyclopentane or cyclohexane) with polycyclic combinations. Aromatic hydrocarbons have consisted of an aromatic nucleus (benzene derivatives) or more aromatic nuclei (poly-aromatic hydrocarbons) (James and El-Gendy, 2018).

In general, aromatic hydrocarbons are the main cause of the eco-toxicological impact of oil pollution on aquatic ecosystems. Resins and asphaltenes represent heterocyclic molecules (N, S, O) with high molecular weight. This fraction also contains metals such as nickel and vanadium. The effects on aquatic fauna and flora are not clearly known and the assessment of such polymers is almost totally excluded from chemical analysis (Marchand, 2003).

The most important physical properties that affect the behavior of a petroleum product discharged into the marine environment are:

- *Density:* hydrocarbons almost always have a density below value 1, which allows them to float (normalized value between 800–1000 kg/m3) (Speight, 2006). However, as a result of aging phenomena (evaporation & emulsification), the density gradually increases to values close to those of water, making their buoyancy more uncertain;
- The distillation characteristics, which have a *flash point* that represents the temperature from which a heated product will give off flammable vapors;
- *The pour point* is the temperature at which it stops flowing;
- *The viscosity* represents the flow resistance, high viscosity hydrocarbons flow less easily than those with lower viscosity.

The viscosity of the spilled oil influences the rate of spill spread, the adhesion capacities of the oil, its penetration into the soil and beach sediments and the ability of pumps used in a cleaning operation to remove oil from the surface (Sivagami et al., 2019).

The table below shows the main properties of petroleum products such as density, viscosity, flash point, solubility, pour point and interfacial tension (Fingas MF, 2000).

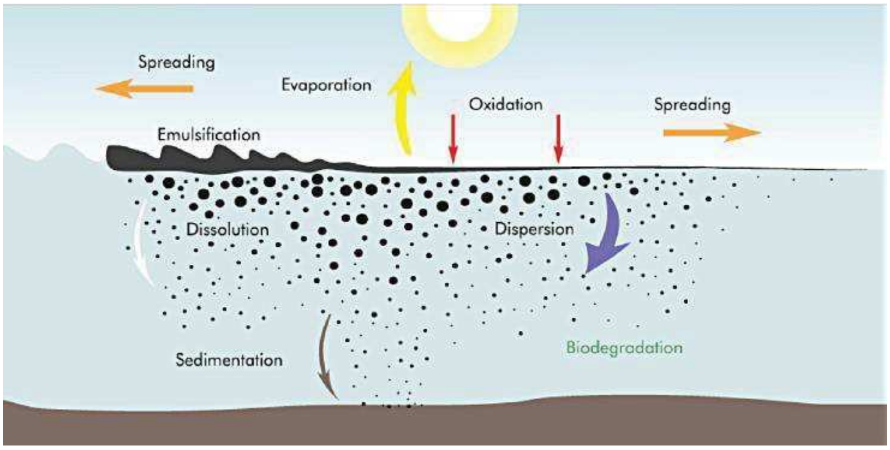
Table 3. Main properties of petroleum products

Property	**Units**	**Gasoline**	**Diesel**	**Light Crude**	**Heavy Crude**	**Intermediate Fuel Oil**	**Bunker C**
Viscosity	mPa.s at 15°C	0.5	2	5 to 50	50 to 50.000	1000 to 15,000	10,000 to 50,000
Density	g/mL at 15°C	0.72	0.84	0.78 to 0.88	0.88 to 1.00	0.94 to 0.99	0.96 to 1.04
Flash Point	°C	35	45	30 to 30	30 to 60	80 to 100	>100
Solubility in Water	ppm	200	40	10 to 50	5 to 30	10 to 30	1 to 5
Pour Point	°C	Not relevant	35 to 10	40 to 30	40 to 30	10 to 10	5 to 20
API Gravity		65	35	30 to 50	10 to 30	10 to 20	5 to 15
Interfacial Tension	mN/m at 15°C	27	27	10 to 30	15 to 30	25 to 30	25 to 35

The transport of a slick of oil is generally induced by the current, the wind, the waves and the turbulent diffusion. Wind and currents are the two major processes that constitute the phenomenon of convection in the marine environment (ASCE, 1996; Jordi et al., 2006; Carracedo et al., 2006; Guo, 2009; Cheng et al., 2011). There are two types of convections: convection at the surface of the water level and surface current. The first one is the slick “floating” generated by wind friction. In this case, an oil slick may move in a direction and speed equal to around 3% of the vector sum and about 100% of the wind speed of the velocity of the current (Reed et al., 1999; Chao et al., 2001; McCay, 2004; Guo et al., 2009; Periáñez et al., 2010).

The second convention runs the water column and it causes hydrocarbon suspended or dissolved particles. However, also the turbulence generated by wave overwash and the shear forces exerted by the coasts and sea floor have the effect to break up the slicks surface and spread it horizontally and vertically.

The most physicochemical processes resulting the change in the physical properties of the hydrocarbon discharged at sea over time (Figure 3).



Source: ITOPF, 2013.

Figure 3. Weathering process of oil spill.

In general, once oil is spilled into the marine environment, it is immediately subjected to a variety of weathering processes that have important effects on the chemical composition of the oil released. There are two distinct phases in this process, a fast phase, including evaporation, dissolution, and a slow phase, including photo-oxidation, biodegradation (Wang et al., 2018; John and Clement, 2016).

Short-Term Evolution Phase

The short-term evolution phase intervenes in the first days and the spill marked is associated with the following components:

Spreading of the Slick

Spreading is one of the most important processes, not only for predicting the extent of pollution but also because it conditions significantly the slick transformation. Indeed, spreading grows the exchange surfaces and increases the mass transfer by evaporation and dissolution. Table 3 represents the three phases of hydrocarbon spreading after spillage over time (Fay, 1971).

Table 4. Phases of hydrocarbon spreading after spillage over time

Phase	Driving force	Resistive force
1	Gravity	Inertia
2	Gravity	Viscosity
3	Surface tension	Viscosity

The spread of a slick involves the forces below (Goeury, 2012):

- Gravitational forces: gravity forces;
- Surface tension forces: surface tensions at the water-air interfaces, hydrocarbon-air, water-hydrocarbon;
- Viscosity forces: viscous friction at the water-oil interface.

The Evaporation of the Light Fractions

Evaporation is the transformation process that generated mass transfer during the first two days for the evolution of the spill. It varies according to the nature of the hydrocarbon, where it can evaporate completely in the case of a gasoline or a diesel fuel, in the order of 40 to 50% in the case of light crude oil and approximately 10 to 15% in the case of heavy fuel oil (Bocard, 2006).

Evaporation is influenced by the nature of the hydrocarbon (density, viscosity), the temperature of the sea water, the wind speed and the slick surface due to spreading.

The Dissolution of the Most Soluble Compounds

Generally, it is estimated that a very small part of the hydrocarbon mass will dissolve in the water. However, the most soluble compounds are often the most toxic, although the dissolution in very small quantities of these substances can have a very strong ecological impact (NRC, 2003).

The physical process of dissolution is well known but the description of a hydrocarbon spill is complex due to the number of components which the product consists of, and, it's a priori necessary to know the dissolution properties of each component (NRC, 2003).

Evaporation also affects dissolution. Indeed, the solubility and volatility of the components are very strongly correlated; the more soluble a compound, the more volatile it is.

Mass transfer due to evaporation predominates on the one due to dissolution. Thus, the mass of the oil slick decreases over time. This depletion within the slick reduces the rate of dissolved material transfer into the water and, in this case, also evaporation of the dissolved components in the water may exist.

A Phase of Long-Term

This phase takes place over weeks, months, or even years. This second phase of evolution is associated with the decontamination of the marine environment as a result of the energy level in the contaminated sites.

Mechanical Energy of the Environment: Natural Dispersion

The dispersal at sea is caused by wave breaking which splits the slick into droplets of different sizes. These droplets are subjected to vertical movements related to their buoyancy and turbulence in the environment. Smaller droplets, with reduced buoyancy, tend to stay in the water column or begin to flow, while the large droplets resurface at the back of the slick. Indeed, surface slick moves by wind and current effects, while the droplets within the water column are moved by current effect. Those move less rapidly than the surface water when resurface, they are located behind the slick (Elliott et al., 1986).

Solar Energy: Photo-Oxidation

Photo-oxidation is a process of oxidation of silk resulting from ultraviolet solar radiation that causes the combination of oxygen and carbons to generate a new product. This process is not well understood how it specifically affects the oils, if it is negligible in the first few hours, it becomes more important after a few days from the spilling accident (Fingas, 2012).

Biological Energy: Biodegradation

Biodegradation is due to the presence of microorganisms in the water such as bacteria, fungi, and yeasts. In fact, they metabolize petroleum hydrocarbons as a source of food energy (Fingas, 2012). This process can take several years because it is extremely slow and highly limited by a few variables such as temperature, oxygen availability, and nutrients (Liu et al., 2012; Fingas, 2012). While some processes are well understood, such as propagation and evaporation, others are not well enough known (photo-oxidation and biodegradation).

ENVIRONMENTAL IMPACTS OF OIL SPILLS

The environmental impacts of oil spills (including fuel oil, gasoline, diesel, and crude oil ...) remain among the most mediatized and environmentally damaging disasters in the world (Walker et al., 2018; Hofer, 1998). These consequences can be identified in several areas: the marine biological and physical environment, human health and society, economy and politics (Etkin et al., 2017; Daly et al., 2016; Bejarano and Michel, 2016).

Oil spills are presented as responsible for terrible consequences for the survival of marine fauna and flora (Etkin et al., 2017; Fingas, 2014). In addition to the negative impacts on the economies and the population living near the contaminated coastline (fishing and tourist activities), they lead to serious impacts and hit the ecosystems hard (Chen et al., 2020; Zabbey and Arimoro, 2017).

The environmental impacts of the oil spill in the marine environment are multiple. There is a direct impact on wildlife through ingestion, inhalation and absorption, and indirect impacts such as loss of habitat or shelter and disruption of natural life cycles leading to the elimination of ecologically important species (Ober, 2010). The environmental impact mechanisms that respond to an oil spill are as follows (Jafarinejad, 2017):

- physical slick with an impact on physiological functions;
- chemical toxicity resulting in lethal or sub-lethal effects or alteration of cellular functions;
- ecological alterations, primarily the loss of key organisms in a community; and
- indirect effects, such as loss of habitat or shelter and subsequent elimination of ecologically important species and disruption of natural life cycles (ITOPF 2014).

The effects of oil spills on the environment depend on several variables such as the location and conditions at the time of the spill, the quantity, the rate and the type of oil spilled, and the safety of the ship (Jafarinejad, 2017). The marine environment depending on geographical location, weather conditions and different seasons can affect both the forms of marine life (number and types ...) as well as the movement, weathering and subsequent toxicity of the spilled oil product itself (Chang et al., 2014; Ramseur, 2012).

The potential effects of a spill often depend on the degree of dilution or dissipation of the pollutant by natural processes (ITOPF, 2013). as well as the timing and geographic location of the affected area where the immediate economic impacts of an accidental marine spill are less than those of spills on beaches near human populations (Chang et al., 2014).

The phenomena of an oil spill generally generate different consequences divided into acute effects ranging from a few days to several years (short-term) and chronic long-term effects, even decades in some cases (Ramseur, 2012). The extent of damage to wildlife caused by oil spills varies depending on the effect and the route of exposure of each organism to the oil or toxic compounds.

Over several decades, the impacts of spills have been studied and documented in the scientific and technical literature. Several studies have demonstrated that the chemical and physical properties of oil undergo alteration, dissolution, oxidation, and volatilization that result in different effects of oil spills on the environment (Neff et al., 2000). For a spill of a large quantity of heavy and dense hydrocarbon (such as heavy fuel oil (HFO)) that is somewhat soluble, the slick that reaches the shoreline after a few days contains virtually only the heavy fraction that becomes entrapped in the intertidal zones of the shoreline and sinks into the water column as sediment, therefore, it can cause considerable damage, while the volatile hydrocarbon (e.g., gasoline) partially dissolves and evaporates rapidly (Walker et al., 2019). Furthermore, the toxicity of the two fractions is not the same or is less likely in the case of HFO or a highly viscous hydrocarbon that is poorly soluble in water due to the low biological availability of their chemical components (McCay et al., 2004).

Other studies show that oil spills pose the greatest threat to marine organisms due to their acute toxicity (Maes, 2004), where thicker oil spills are considered the most damaging to the environment (McCay et al., 2004). Oil spills pose the greatest threat to birds and marine mammals, due to their effects on skin or feathers (Vidal and Domínguez, 2015; Hofer, 1998; Williams et al., 1994), as well as its negative effects on the digestive, respiratory and circulatory systems due to ingestion or inhalation of toxic petroleum products (Hofer, 1998).

The consequences of the pollution of aquatic environments are multiple. They lead to mass mortality of species, but they also have less visible effects: eutrophication of the environment, more or less long-term toxic effects, diseases, or endocrine disruption (Singh et al., 2020). The main impacts of oil spills on the marine environment may be related to the different species.

Birds

Seabirds and shorebirds are considered extremely vulnerable and sensitive to oil spills due to the great effects on their skin or feathers, which can lead to drowning and hypothermia (Tran et al., 2014), as well as their flight performance and reproduction (Perez et al., 2017). Due to its toxic effects, spills can have long-term chronic impacts in birds, such as morality, pathological disturbances and malformations of the lungs, liver, kidneys and glands (Troisi et al., 2016).

As a result of the Amoco Cadiz spill in March 1978, between 3,000 and 4,000 dead birds were collected. Thus, during the Exxon Valdez spill in 1989, more than 30,000 seabird carcasses were found in the Gulf of Alaska (Boersma et al., 2001). The impact is highly dependent on the season and the area affected, in the case of the Erika shipwreck in 1999, it is estimated that 150,000 birds were killed by oil (Goeury, 2014).

Fish

In the case of aquatic species, on the other hand, they are affected differently. Exposure of fishes to hydrocarbons even at very low exposure concentrations can result in fatal impacts such as cardiac dysfunction, aeration problems, morphological imperfections, acute cardiotoxicity and decreased swimming speed (Incardona et al., 2013; Hicken et al., 2011). A large literature shows that exposure of fish to hydrocarbons can cause genetic damage, reduced growth and feeding rates and mortality of fish eggs and larvae (Langangen et al., 2017; Fingas, 2012; Meier et al., 2010).

Marine Plankton

The main victims of oil spills are fixed species such as marine planktonic organisms. The exposure of phytoplankton and zooplankton communities to oil can lead to deleterious effects (Daly et al., 2016;

Kleindienst et al., 2015; Garr et al., 2014; Jiang et al., 2010). It can lead to immediate mortality, decreased feeding, acute and chronic toxicity, disturbances and malformations in reproduction and egg production, reduced swimming speed and altered physiological activities (Hansen et al., 2015; Kleindienst et al., 2015; Almeda et al., 2014; Cohen et al., 2014; Ortmann et al., 2012).

Mammals and Reptiles

The exposure of marine animals (turtles, dolphins, crocodiles, etc.) to oil spills, especially in the open sea, can cause serious impacts such as hypothermia, drowning and death (Singh et al., 2020; Venn-Watson et al., 2015), as well as kidney abnormalities and lung disease (Schwacke et al., 2014) due to toxic compositions that penetrate the outer surface of mammalian fur and in growing embryos for turtles (Putman et al., 2015).

Vegetation and Marine Environment

Oil spills impact the marine environment and its biodiversity, they cause significant impacts on aquatic plants, micro and macro-algae, seagrasses, kelp forests, and shrubs (Singh et al., 2020; Duke, 2016). Exposure to hydrocarbons can smother the pneumatophores of the roots by covering them, decreasing the oxygen flow in the roots, which ultimately leads to starvation and death (Lewis et al., 2011). It can cause impacts on vegetation such as wilting, senescence and leaf loss, root deformation, reduced efficiency of photosynthesis, eco-toxicological effects, and significant mutations (Naidoo et al., 2010). The study of Turner et al., (2014) shows that oil contamination of marsh vegetation by oil induces stress to the plants and the water content of the vegetation cover. Exposure to oils in coral communities leads to adverse impacts due to oil toxicity which can cause problems such as smothering, malformation, coating, growth retardation, and reduction in lipid content (Fisher et al., 2014).

On the other hand, the interventions of clean-up teams can degrade a fragile environment through the use of chemicals, high-pressure water jets and the mechanical removal of the surface layer of sand destroying the higher organisms that would have resisted the oil and slowing down very sharply the recolonization of the impacted area, thus creating a biological desert. The experience of Torrey Canyon in 1967 showed that clean-up operations could be more destructive in the medium term than the oil spill itself (Goeury, 2014; Ober, 2010; De La Huz et al., 2005).

OIL RESPONSE METHODS

In order to respond to an oil spill, it is necessary to implement substantial resources according to strategic choices that take into account the nature of the spilled product, the site of the accident, the weather conditions and the environmental characteristics (Singh et al., 2020; Gong et al., 2014; Dave and Ghaly, 2011; Lessard and DeMarco, 2000).

In general, the response can be divided into three stages: containment, oil recovery and the cleaning of soiled surfaces. For the purpose of minimizing the catastrophic impacts of oil spills, several techniques are being developed for oil spill response for containment and recovery, including mechanical techniques, use of dispersants and solidifiers, bioremediation and burning (Singh et al., 2020).

In fact, all oil spill response recovery has a certain impact on the environment, so the decision to select a clean-up method requires a trade-off between the effects of the oil spill and the side effects of clean-up (Dave and Ghaly, 2011). In this section, some of the procedures commonly used in the clean-up of oil spills are presented.

Containment and Recovery Operations

The containment and recovery operations together constitute a series of actions that optimize the effectiveness of the intervention and therefore they minimize the associated environmental impacts. The purpose of containment is to slow down the movement of oil on water or redirect it in order to regroup and concentrate it to optimize the efficiency of recovery operations (Prabowo and Bae, 2019; Fingas, 2013). Also, diverting the trajectory of the oil slick allows it to be moved away from sensitive resources, thus reducing environmental impacts (ITOPF, 2012). Although the efficiency of containment and recovery operations is defined as the quantity of oil removed from the surface or from the water column. It may be interesting to include in the efficiency analysis the extent of the environmental impacts generated by the intervention (Barsauskas, 2014). In general, three methods are considered during an oil spill on the high seas: physical recovery, the use of dispersants and in-situ burning (Bocard, 2006).

Physical/Mechanical Methods

Skimming, vacuums, as well as the use of booms or barriers, bubble or air-jet booms, are methods of physical-mechanical recovery (Singh et al., 2020; Barsauskas, 2014). The choice of a physical-mechanical recovery method depends on the nature of the spilled oil, the weather conditions and the location of the spill (Prabowo and Bae, 2019; Bocard, 2006). Indeed, the oil must be mobilizable, pumpable and therefore not too viscous, otherwise, the efficiency of operations may be greatly reduced (Doshi et al., 2018).

Booms, also known as containment booms, make it possible to confine spilled oil slicks in order to reduce the risks of pollution and safeguard the marine environment where they can easily deviate the trajectory of the oil spill to protect vulnerable ecosystems (Pagnucco and Phillips, 2018; Doshi et al., 2018; Castro et al., 2010). In addition, vessels commonly used by ships that pass through the heaviest parts of low-speed spills collect the oil in thicker layers for quick and easy recovery at the water surface (Dave and Ghaly, 2011). They are composed of three main configurations: fence booms, fire-resistant booms and curtain booms (Singh et al., 2020; Dave and Ghaly, 2011). Among the most commonly used booms are shoreline booms, ice booms, absorbent booms, and inflatable booms (Singh et al., 2020).

Skimming consists of removing (by pumping) large accumulations of floating oil from the water surface in the event of a major spill or even the entire slick (Prabowo and Bae, 2019). It is based on the action of mechanical equipment adapted to the environments in which they intervene (Fingas, 2013). It is generally used in combination with booms and mostly it consists of a reservoir for collecting and settling the oil after its removal (Michel and Fingas, 2016). They are divided into three types: weir skimmers, suction skimmers, and oleophilic skimmers (Singh et al., 2020; Michel and Fingas, 2016). Their main advantage is that skimmers can operate in bad weather and do not change the characteristics of the oil (Michel and Fingas, 2016).

The most applicable and widely used technique for oil spill response is adsorption by sorbents due to their high capacity of sorption and selectivity (Wu et al., 2014). They are hydrophobic and oleophilic materials that absorb oil by soaking and separating it from water (Yang et al., 2014; Xue et al., 2013). In addition, adsorbents are different in properties such as recyclability, density wettability and sorption capacity of oil (Bhardwaj and Bhaskarwar, 2018; Doshi and Kalliola, 2018). They are divided into three main categories: natural organic adsorbents (Lv et al., 2018; Angelova et al., 2011), natural inorganic adsorbents (Ceylan et al., 2009; Carmody et al., 2007), and synthetic adsorbents (Pinto et al., 2018).

Chemical Methods (Dispersants)

Dispersants are chemical agents applied to oil slicks to break them into smaller droplets (Fingas, 2011) and to promote the creation of oil droplets that disperse through the water column, both vertically and horizontally (Michel and Fingas, 2016; Atlas and Hazen, 2011). The purpose of this technique is to generate the natural dispersion of oil in favor of its emulsification to dilute concentrations in the water column and to accelerate the rapid biodegradation of oil by dilution (Atlas and Hazen, 2011).

The efficiency of a dispersant depends mainly on the composition of the oil, its viscosity, the dosage of the dispersants used, the temperature, and the energy of the sea (NRC, 2005). The dispersants cannot be used for highly viscous oil and stable emulsions (ITOPF, 2011).

When containment and recovery are difficult due to environmental conditions (Michel and Fingas, 2016) may be useful to limit the impact on more sensitive areas and organisms found at the shoreline (ITOPF, 2011). However, the toxicity and long-term effects of dispersants are widely debated within the scientific community (Fingas and Banta, 2008).

Thermal Remediation

In-situ burning is a more efficient option because it allows the removal of large quantities of spilled oil in a single step without the use of specialized machinery, within an acceptable time frame (M. Fingas, 2013). It is strongly influenced by meteorological conditions such as temperature, wind speed and waves, as well as other parameters such as the type and weathering of the oil, the thickness of the oil slick and the presence of oxygen (Ndimele et al., 2017).

The main advantages of this method are its effectiveness in the case of light petrol spills that burn without causing effects to marine life, as well as for oil slicks that cover a large area in calm weather conditions, thus avoiding the movement of the slick to sensitive areas (Evans et al., 2001). On the other hand, the residues left behind can be removed by any mechanical means (Singh et al., 2020).

Regarding the drawbacks of this method, burning generates toxic atmospheric emissions that contain harmful residues which can precipitate and thus interact with environmental organisms (M. Fingas, 2013) generating risk to human health and the environment and especially to the organisms living near the damaged site (Prabowo and Bae, 2019).

Cleaning Operations

Clean-up operations may be required to prevent damage and contamination of shorelines and beaches following a spill, even if oil containment and recovery operations have taken place. Indeed, clean-up operations can sometimes be quite intrusive and can cause considerable environmental impacts (Fingas, 2013; Bocard, 2006). The choice of this operation depends on several factors such as the sensitivity of the environment, potential habitats to be cleaned up, ecological and socio-economic factors. Clean-up can be carried out using the following techniques (Michel and Fingas, 2016):

- Manual cleaning;
- Physical methods;
- Sediment remobilization;
- Washing by water jet, sandblast, and steam;
- Flooding of sediments.

Biological Methods

Biological methods are widespread in marine ecology, they are based on the optimization of natural microbial action without producing negative impacts They aim to stimulate the capacity of particular microorganisms to degrade the hydrocarbons that are present at the site of the oil spill (Prince and Clark, 2003). Two types of biological methods can be distinguished, including bioremediation and biodegradation (Singh et al., 2020; Silva et al., 2014).

The bioremediation process is the addition of specific microorganisms (bacteria and fungi) to increase the rate of biodegradation in a given media (Fingas, 2013; Dave and Ghaly, 2011), as well as to degrade and metabolize chemical substances and restore environmental quality (Singh et al., 2020). Biodegradation consists of amending the environment where the spill occurred with insufficient nutrients in the existing conditions

(Wang et al., 2017; Nyankson et al., 2015), thus resulting in the activation of the microflora and stimulation of the biodegradation of the oil (Barsauskas, 2014). In addition, it is affected by certain environmental factors such as oxygen availability, PH, water salinity, temperature, and nutrient composition (Singh et al., 2020).

CONCLUSION

The objective of this chapter is to examine the catastrophic effects of oil spills at sea on the environment and to present the various response methods in the event of an accident. Indeed, the environmental impacts of oil spills in the marine environment have been studied in the scientific literature in recent decades, where it is becoming clear to estimate the extent and duration of the damage caused by a particular accident. These impacts pose a challenge to the survival of ecosystems and biological diversity which can be mainly direct on wildlife through ingestion, inhalation, and absorption, or indirectly such as loss of habitat or shelter and disruption of natural life cycles leading to the elimination of ecologically important species.

Furthermore, the response to an oil spill requires the implementation of significant resources according to strategic choices that take into account the nature of the spilled product, the location of the accident, weather conditions, and environmental characteristics. In general, the response can be divided into three stages: containment, recovery of the oil, as well as cleaning of soiled surfaces. For this reason, and in order to minimize the catastrophic impacts of oil spills, several techniques have been developed for oil spill response for containment and recovery, including physical mechanisms, the use of dispersants, bioremediation, and burning.

In fact, all oil spill response methods have some impact on the environment, so the selection of a clean-up method requires a compromise between the effects of the oil spill and the side effects of clean-up, taking into consideration minimizing both the environmental impact and the cost of the operation.

The uniqueness of each spill can provide additional information on pollutant behavior and ecosystem responses. Thus, the evaluation of response methods and environmental monitoring can be part of a continuous improvement approach. Consequently, contingency plans, response measures, and decision support frameworks must be developed, as well as the establishment of methodologies to ensure the quality and rehabilitation of the environments affected by the incident in order to safeguard aquatic biodiversity. In this context, the identification of benchmarks to guide the evolution of response operations through visual and measurable criteria is required.

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