Environmental Implications from Deep Sea Oil Release

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School of Chemical and Environmental Engineering, 2023

Acknowledgments

I would like to thank Supervising Professor Kalogerakis Nicolaos for the opportunity he gave me to be part of such a fascinating project. I'd also like to thank Dr. Antoniou Eleftheria for providing guidance when required and PhD candidate Fragkou Voula for her comments throughout this project.

I am also thankful to my family, especially my wife for her patience and all the support and my two beautiful children for all the love and joy in my life.

Finally, I would like to thank my parents for keep watching and guiding me from above…

Abstract

This thesis focuses on management issues of anthropogenic, natural disasters or accidents that lead to the occurrence and appearance of oil spills on the surface or the bottom of the sea. In particular, emphasis is placed on the factors that contribute to water or subsoil pollution in general, and how such issues are addressed with the aim of bringing together the emerging data on the management of petroleum-derived or by-derived contaminated wastewater and explaining the challenge and the best methods of their management. A main finding that emerged is that early prediction, appropriate engineering design, the availability of waste and toxic substance removal tools and technologies, and simulations contribute to the appropriate management of similar crises. However, how such accidents will be managed depends on the data of each incident such as, among others, the depth and extent of the destruction, the causes of the accident, environmental and weather conditions (wind strength, temperature, visibility, pressure) as well as the applicable legislative framework in an area. Then, using the Deepwater Horizon accident as a case study, it is found that the management of similar crises is an important project with an impact on the quality of life of citizens, the environment and international relations. This conclusion was reached because it was found that the difficulty in managing similar crises can lead to environmental disasters, energy shortages, loss of biodiversity, reduction of tourist traffic as well as human lives. So, the effects of such accidents are direct and indirect, short-term and long-term, and often costly and time-consuming. The Deepwater Horizon accident, being at a depth of 1,500 meters, was particularly difficult to deal with since water pressure, accessibility, visibility and the possibility of containing the oil in one area were limited. This accident, one hopes, will be an example to avoid for the future and a sample of the need to improve the methods of prevention, simulation and management of corresponding emergencies.

Keywords

Deepwater Horizon, oil spills, oil drilling, accidents, spillage, stimulations, bioremediation, oil, hydrocarbons.

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Introduction

The rapid development of engineering technology, transportation, and industrial production, as well as the widespread urbanization that began to be observed from the 18th century and peaked, as phenomena, in the 20th century, led to a dramatic increase in energy needs. Humanity, additionally, is growing in numbers and spread, and these persons use energy in their daily lives. Also, in addition to the above, energy is required for almost every human activity that does not concern just their private but their public life as well (Goldstone, 2002).

Hydrocarbons, as a conventional energy resource, are widely used worldwide. Since the discovery of oil prospects, special emphasis has been placed on discovering new energy reserves, understanding the characteristics of areas with oil reserves, exploiting these reserves as well as transferring the fuel from an area to the other. This has led to a search for sources on land and in the sea. Oil sources located at great depths require, for their exploitation, specific projects that must be done in order to extract the oil and refine it (Abou Khalil et al., 2021; Barclays, 2015; Soliman-Hunter, 2019; Tamburrino, et al., 2019).

Both deep-sea exploration and the search for oil extraction methods can have an environmental impact. This impact is related to the disruption of the ecosystem as well as the direct contamination due to the transport of raw materials in the area. The process of transportation itself requires the use of fuel, while the transportation of oil to large cities through pipelines or by waterborne means causes pollution and environmental burden (Ministry of Environment and Forests, 2009; Soliman-Hunter, 2019).

The research also discusses the environmental impact of an oil spill on the seabed in the event of an accident. Accidents often take place at shallow depths and are therefore treatable. However, the deeper the water, the more difficult the weather and environmental conditions in an area, and the greater the distance from land, the more complex are the accidents and incidents that take place on the seabed (Lee et al., 2016).

For those in charge, dealing with such incidents is a responsibility and an obligation arising from both the law and the applicable company statutes. This obligation is towards man, towards the environment and towards the company itself. The more prepared the agencies are for potential accidents and crises, the more likely it is to avoid an emergency that would bring about extremely costly and dangerous results (Lee et al., 2016; Ministry of Environment and Forests, 2009).

In this study, all the above issues are analyzed with a focus on four different questions that the paper attempts to investigate. These questions are the following:

Q1: What are the main deep-sea pollutants and incidents that can cause oil spillage and other types of pollution?

Q2: What is the impact of deep-sea oil releases on the environment, both the natural and the human?

Q3: How do experts tackle accidents and incidents that cause oil spillage and what are the main challenges associated with their management?

Q4: Using Deepwater Horizon as a case study, what conclusions can be reached regarding managing offshore activities regarding oil drilling and transfer?

The basic methodology used is that of a bibliographic review using a multitude of references from the international literature. Emphasis was placed on the research of multidisciplinary studies for the analysis and the utilization of reports concerning different regions of the planet such as, among others, the Pacific, Southeast Asia, the Arctic and the Gulf of Mexico.

Chapter 1

Deep-sea pollutants

In this first chapter of the study, reference is made to causes that lead to water pollution, both on the surface of the water and, mainly at the bottom of the sea. While primarily emphasis is placed on human activity such as accidents, voluntary actions and human error, parameters that lead to the contamination of water by pollutants, reference is also made to natural phenomena that contribute to water pollution. Such phenomena, however, are studied with the criterion of how they lead to an accident and an oil spill in an area. They are referred to as "natural" because they arise without human intervention.

1.1. Heavy metals and toxic waste

Regarding the problems that arise during drilling, according to Harris et al. (2016), the waters are polluted with toxic waste and heavy metals. In detail, studies in areas near the Norwegian shelf, where significant oil reserves are located, it is observed that there is contamination of the waters in a diameter of 2 to 6 km away from the platform. The chemical elements referred to as pollutants in these areas are cadmium, copper, zinc, barium and lead. The discovery of these elements led to a ban on activity in areas of the North Sea and an increase in recommended distances for rigs near populated areas.

According to Kumar, Rajan, Kirubagaran & Dharani (2019), complex oil/hydrocarbon mixtures pollute the seabed in different ways. Toxic waste results from accidents, such as the sinking of ships, cracks in disposal facilities as well as other causes, accidental or not. Addressing these contamination phenomena and incidents is extremely important for the protection of biodiversity and human societies. Areas with high levels of poverty are particularly vulnerable to such accidents (WWF, 2018).

Generally, according to Jroundi, Martinez-Ruiz, Merroun & Gonzalez-Muñoz (2020), human activity has led to the change of the chemical composition on the earth's biosphere. To date, it has been established that the pressure caused by the rapid increase in human activity has led to changes in the composition of microbes, chemical elements, and the subsoil of the seabed, even at a depth of 1000 meters. What makes it important to study the effects of human activity on the seabed, is that at least 67% of the earth's crust remains incompletely known to man.

It is therefore necessary for the competent agencies to effectively recognize the events that took place and propose strategies that will be successful in the appropriate space and time. Locating oil spills on the seabed is a challenge both for the companies responsible for causing the problem and for the states located near the site of the accident or incident that caused the spill (White, Conmy, MacDonald & Reddy, 2016).

According to "The International Ocean Discovery Program" (2013), for the future of the planet it is an important task for companies and institutions to reflect on the importance of pollution management, both from heavy metals and from toxic and harmful to human health substances. Deposits of such substances on the seabed and diffusion of them into the sea, occur due to both negligence and accidents. The diffusion of these causes long-term consequences in climate change as well as in the natural environment.

Heavy metals and toxic substances are deposited on the seabed due to the fact that human activity increases near areas inhabited by a large population or there is intense industrial activity. Certain industries and sectors of activity are more likely to harm the environment as well as produce more waste. Especially in areas with moderate legislation, it is more likely that this waste will end up in bodies of water. Managing and limiting pollution from liquid and solid waste deposited in water bodies becomes a particularly difficult task because limiting their dispersion is a costly and risky challenge (International Ocean Discovery Programme, 2013).

According to Lloyd-Smith & BAppSc (2018), the effect of the use of chemicals and other biological agents on crops and human activities is also important. For example, the use of insecticides and growth factors in crops is considered particularly dangerous for the environment and the ecosystem, since checking whether these are found, and their removal is a particularly complex task.

1.2. Shipment and wreckages

Correspondingly, the impact of human activity related to the transport of goods using sea routes is high. The use of sea routes presupposes the use of a mean of transport which pollutes the atmosphere and waters because it uses fuel. The use of both fossil and non-fossil fuels leads to cumulative pollution of the biosphere and waters (Lloyd-Smith & BAppSc, 2018).

It is noted that, beyond the transport sector, also in the process of construction and exploitation of oil and natural gas refining platforms there is a risk of pollution due to the movement of ships. The reason is that most of the time, the components and mechanisms required for the construction of a floating hydrocarbon exploitation station are transported by ships (European Commission, 2019).

There is also the risk of contamination, pollution and accidents due to the movement of ships, especially in particularly important areas for the environment and humanity such as the Arctic. Shipping by ship carries risks such as contamination and accident. An accident involving a floating oil carrier can have a significant impact on the environment. The impact on humanity will be immediate because, in a shipwreck or boating accident, there is a loss of human life, as well as because it leads to the contents of the ship ending up at the bottom of the sea (European Commission, 2019).

There are many examples of accidents involving oil tankers around the world that led to an oil spill, thus pollution of the marine environment. Accidents such as the Exxon Valdez accident (1989) in the Arctic which led to a release of 37,000 tn of crude and a huge ecological disaster, the Atlantic Empress (1979) in the Caribbean, and the Agia Zoni II (2017) in the Saronic Gulf in Greece. Unfortunately, the list of such accidents is big, and the amount of oil that has ended up in the marine environment is enormous.

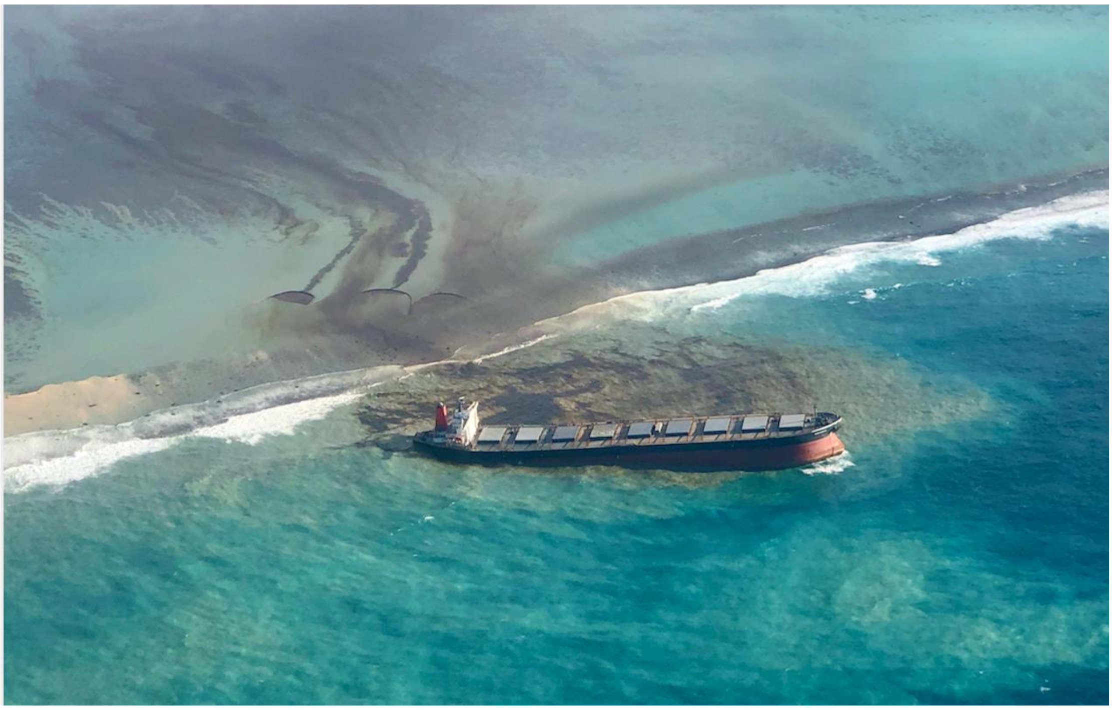


Figure 1. An aerial view taken on August 8, 2020, shows a large patch of leaked oil from the MV Wakashio off the coast of Mauritius (AP Image)

1.3. Natural phenomena

In the previous paragraph, references were made to accidents and anthropogenic factors that can lead to seabed contamination. However, a water pollution/contamination can also result from natural causes. One such natural cause is the eruption of volcanoes and earthquakes that can lead to deep sea hydrocarbon seepages. Also, natural phenomena such as tsunamis can lead to accidents which cause either physical damage to places where refining is done, or accidents (wrecks or damage to ships and transport) or the transfer of a spill from one area to another. In this way, there may be a gas or oil leak on the seabed, pollution of the atmosphere and water as well as disruption of fauna and flora and an ecosystem (European Commission, 2007).

Figure 2. Oil leaked from a Nippon Petroleum Refining Co. oil factory float at Shiogama bay, Miyagi prefecture, a day after one of Japan's strongest earthquakes ever recorded hit the country's east coast. (AP Image)

Natural dispersion of oil in small amounts in the atmosphere has been taking place for millions of years and microbes can use the hydrocarbon seeps to feed. Therefore, oil, although in large concentrations it can be toxic, does not necessarily mean that it will lead to atmospheric and/or environmental pollution. However, as the use of oil by industry and the average person increases, so does the risk of environmental pollution (Abou Khalil et al., 2021).

Similarly, according to Harris et al. (2016), oil spills caused either by accident or during drilling have serious potential environmental impacts. There are risks involved in the process of setting up an installation, and also there are concerns of pollution from the transportation, from the process itself, and last but not least, the risk of a natural disaster, such as of a seismic activity, in the region of drilling. Therefore, there are also natural factors and frequent hazards that are not linked to any accident or intentional act and cause significant problems to marine life, fauna, flora, and humans.

Natural disasters are a particularly important risk when a platform is being built or an oil transfer process is taking place. For example, in 2005, Hurricane Katrina resulted in the destruction of one hundred and thirteen (113) platforms and four hundred and fifty-seven (457) oil and gas pipelines. The destruction was so vast, that to this day is considered impossible to measure the impact and it has not been possible to record the total tons of hydrocarbons spilled into the environment (Harris et al., 2016).

In the form of an image, naturally occurring processes are described in detail and comprehensively (European Commission, 2007. The processes that are presented in the picture show the generation of thermogenic oil and deeper gas and the generation of biogenic methane. The generated gas is consumed by anaerobic or aerobic microorganisms, but it can also escape to the atmosphere.

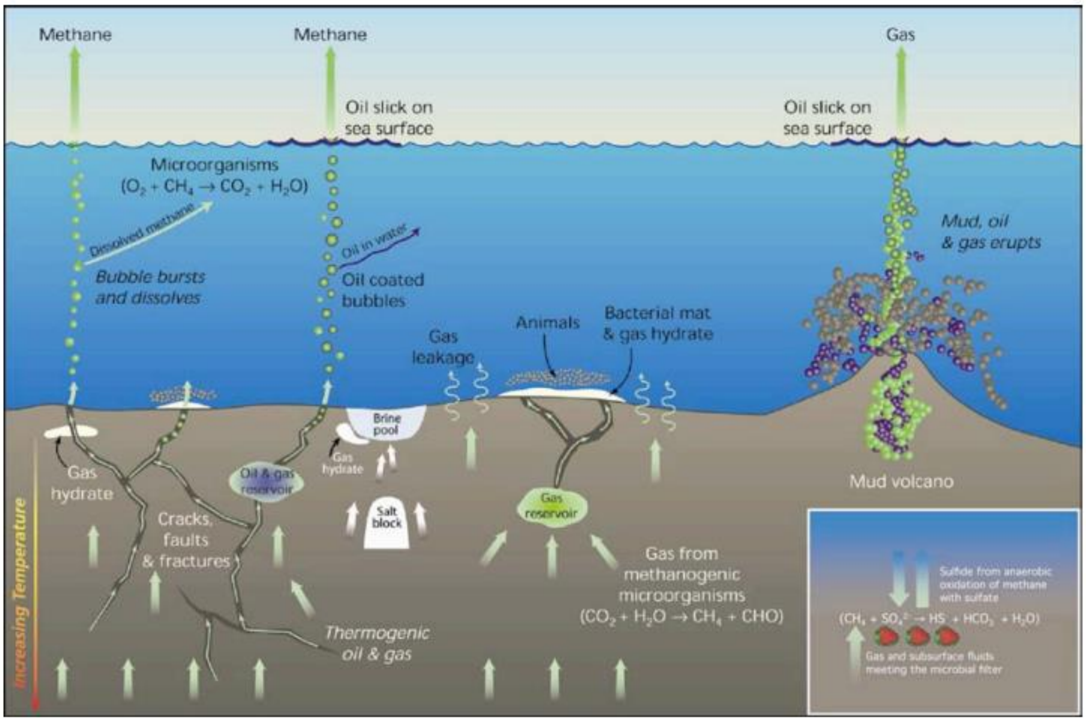


Figure 3. Natural processes, European Commission, 2007, p. 16

The presence of toxic substances is a frequent phenomenon in the seabed. Such toxic substances are heavy metals, organic compounds such as PAHs and PCB, chemicals and microplastics, as well as gas releases produced in large quantities by underwater volcanoes. These substances are harmful to the marine environment, but also to human health.

1.4. Oil releases

As a substance, oil has specific properties and characteristics that one must consider when studying the environmental impact of an oil spill on the seabed in different ways. Oil covers the surface of the water in large quantities and makes the area where oil was deposited highly toxic for the marine ecosystem and the human health. Also, if a large amount of oil has been spilled in an area, then the fauna in that area is directly affected (Galil & Herut, 2011).

Other types of accidents can also occur at coal and hydrocarbon sites. Purser & Thomsen (2012) refer to four possible types of accident:

(1) the direct mechanical damage,

(2) damages during drilling,

(3) water pollution due to the waste of production products and,

(4) acute accidental exposure to pollution due to oil/hydrocarbon spills.

Depending on the case, different procedures for the management and prevention of possible accidents in a pipeline and an onshore or offshore installation will indeed be chosen. According to the Ministry of Environment and Forests (2009, p. 26), during the process of exploitation of coal and hydrocarbons, the main pollutants that diffuse into the atmosphere are nitrogen oxides, sulfur oxides, carbon monoxide, methane, ethane, benzene/ethyle benzene, toluene and xylenes, glycols, and polycyclic aromatic hydrocarbons.

The threat of a technical accident due to human error accompanied by a small risk of leaking a large amount of fuel and toxic waste into the sea is considered a "simple threat". A simple threat is also considered the possibility of leakage into the water from damage to the pipelines or accidents. More complex is the threat of errors during drilling. Drilling at depth can result in permanent cracks that could lead to an uncontrolled release of hydrocarbons in the sea.

According to the European Commission (2019, p. 41), the main causes of accidents in offshore installation areas are the following:

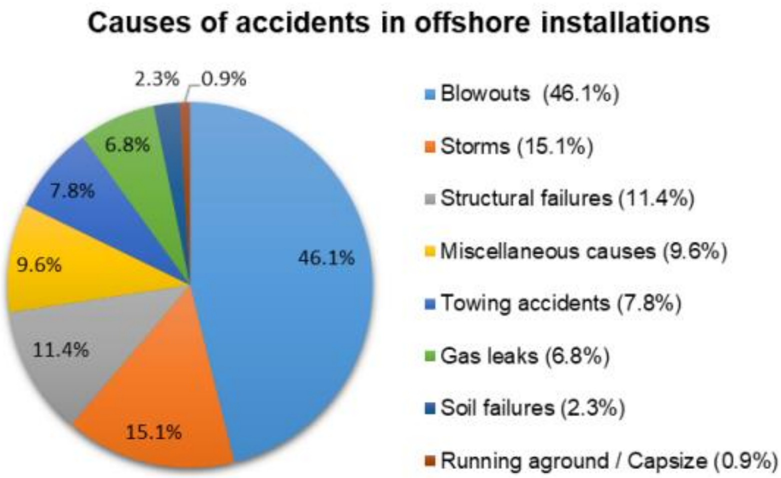


Figure 4. Main causes of accidents in offshore installations, source European Commission, 2019, p. 41.

It turns out that almost one in two accident cases are attributed to blowouts, while the less frequent accidents concern soil failures (2.3%) and running aground (0.9%). So, a simple threat is more likely to develop into a crisis than a complex one. This is particularly important because simple threats are easier to manage.

Also, a serious accident that can occur in a floating refinery platform area is fires. Fires can cause both air pollution and serious loss of life mainly due to explosions and toxic gases. For the facility, fire control can be easier when all safety systems are properly anticipated and implemented. However, a serious accident can develop into a very serious problem for human safety.

Figure 5. On July 6th, 1988, the Piper Alpha North Sea oil platform suffered a massive leakage of gas condensate (AP Image)

According to EMSA (2013), well blowouts are a major cause of sea bottom contamination in offshore facilities. Well blowouts occur both on the surface of the water and on the seabed, with surface blowouts typically occurring at the installation site and being detected more quickly than sub-sea well blowouts which occur on the seabed and cause the spill to spread quickly and before the need for management is realized.

Typically, most well blowouts are small in extent but not of limited human impact. It is particularly important to mention, that well blowouts that occur in very deep waters can make the operation of restoring and cleaning the bottom particularly difficult. Therefore, managing this challenge is both costly and complex in relation to the necessary cleanup technology and strategy (EMSA, 2013).

According to the Ministry of Environment and Forests (2009), what was the process that was followed that caused the contamination also plays a crucial role. For example, it matters if the industry segment that was affected concerned upstream segment deals (oil and gas exploitation and production), midstream deals (transport) or downstream deals (i.e., refining and processing).

According to Barclays (2015, p. 3), upstream and downstream processes can be described and distinguished as follows:

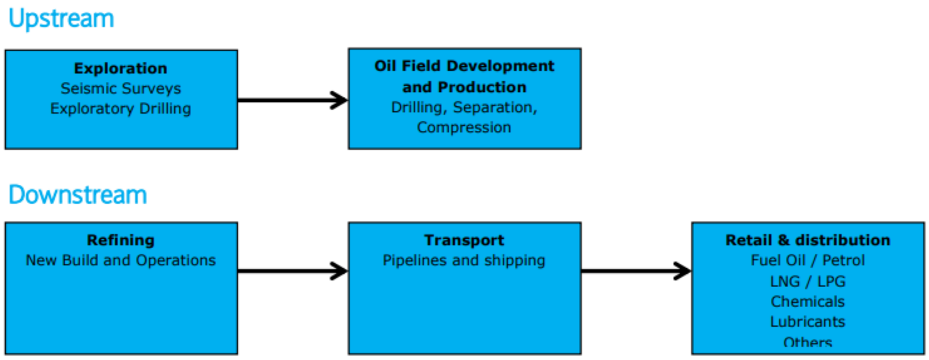


Figure 6. Upstream and downstream processes, source, Barclays, 2015, p. 3

Also, the exploitation of oil leads to water pollution through the diffusion into the environment of the by-products/waste of the production. This process of refining and processing, especially of oil, leads to widespread contamination of the areas near the installation of exploitation of mineral resources. Waste reduction is considered particularly important to limit the environmental impact of crude oil exploitation (Ministry of Environment and Forests, 2009).

For the main pollutants that burden the quality of water in areas with a leak or extensive oil exploitation, it is noted that the extent to which the quality of the water will be affected and cause long-term effects on the quality of life of the individual, is also related to the basic properties of the oil. Therefore, the various chemical and biological methods of oil removal will be applied in a different way. The chemical composition of crude oil is such that four (4) are its main chemical fractions- saturates, aromatics, resins and asphaltenes. These substances affect the natural balance of the seabed and the marine environment in a different way (Lee et al., 2016).

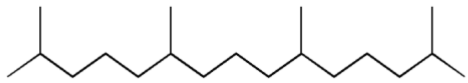
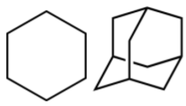
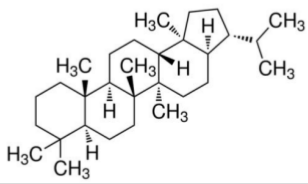
Name of chemical class or fraction	Example of class or fraction	Structure of example compound(s)	Properties and relevance of class or fraction
SATURATES			Usually the most abundant chemical class in petroleum; highly water-insoluble; typically are biodegradable and generally non-toxic
n-Alkanes	*n*- Hexadecane		*n*-Alkanes <C_6 are light liquids or gases and may be toxic; C_6-C_{18} are readily biodegradable; >C_{20} are waxes and more difficult to biodegrade
iso-Alkanes	Pristane		*iso*-Alkanes are more resistant to biodegradation than *n*-alkanes; some, such as pristane and phytane, are used as short-term biomarkers for aerobic biodegradation
cyclo-Alkanes and Diamondoids	Cyclohexane; Adamantane		More resistant to biodegradation than *n*-alkanes; diamondoids may be used as robust biomarkers during biodegradation (de Araujo et al. 2012)
Hopanoids and Steroids	17α(H),21β(H)-Hopane (30αβ)		Many are non-biodegradable and therefore are used as long-term biomarkers for forensics and biodegradation assessment

Figure 8. Main categories of saturates in petroleum products and their properties, source Lee et al., 2016, p. 56.

In detail, saturates are the least toxic compounds of oil for humans and the environment and easily biodegrade, so it is one of the least concerns for those responsible for managing an oil spill or similar accidents. Then, aromatics are more toxic than saturates and are likely to be more volatile and more carcinogenic than saturates. Therefore, they are more dangerous for humans (Lee et al., 2016).

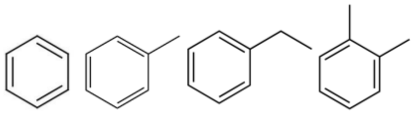
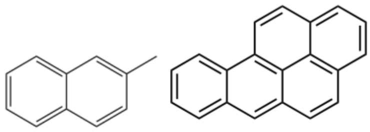
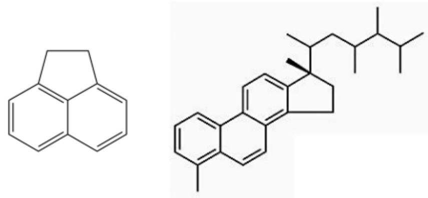
Name of chemical class or fraction	Example of class or fraction	Structure of example compound(s)	Properties and relevance of class or fraction
AROMATICS		The examples shown below are strictly hydrocarbons; however, some aromatics having heteroatoms (i.e., S-, N- and O-heterocycles) fractionate with the aromatic hydrocarbons and are often considered together functionally. Examples of such aromatic heterocycles are shown in the resins fraction below.	A hydrocarbon class that is generally more toxic than saturates; many isomers and homologous series are possible when aliphatic groups are attached to the aromatic rings.
Monoaromatics	BTEX: Benzene, Toluene, Ethylbenzene and Xylene isomers (*ortho*-xylene shown)		The BTEX series is volatile, more water-soluble than other hydrocarbons, acutely toxic and/or carcinogenic, and relatively biodegradable under aerobic and anaerobic conditions
Polycyclic aromatic hydrocarbons (PAHs) and alkylated series (alkyl PAH)	2-Methylnaphthalene and Benzo[a]pyrene		Large number of isomers are possible due to multiple positions for alkyl side chains; some PAHs are toxic and/or carcinogenic; many persist in the environment because they resist biodegradation; benzo[a]pyrene is a US-EPA 'Priority Pollutant'
Naphtheno-aromatics; aromatic steroids	Acenaphthene and a triaromatic steroid		Combination of saturated and unsaturated cyclic hydrocarbons; acenaphthene is a US-EPA 'Priority Pollutant'; triaromatic steroids have been used for forensic attribution of environmental contamination

Figure 9. Main categories of aromatics in petroleum products and their properties, source Lee et al., 2016, p. 57.

Then, for resins, it is noted that they are closely related to asphaltenes and have a lower molecular weight. The challenge in the case of resins is that they are difficult to locate in water (Lee et al., 2016).

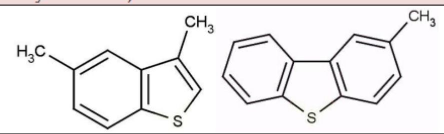
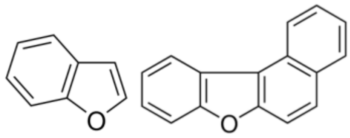
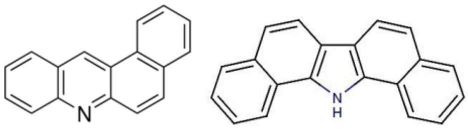
Name of chemical class or fraction	Example of class or fraction	Structure of example compound(s)	Properties and relevance of class or fraction
RESINS		The structures of individual resin compounds have not been determined, but they contain one or more S-, N- and/or O-heteroatoms; examples of aromatic S-, N- and O-moieties that may form part of resin structures are shown below. The individual chemicals below are commonly considered to be part of the Aromatics fraction (despite being heterocycles rather than hydrocarbons).	A solubility class related to asphaltenes (below), but of lower molecular weight, lower aromatic content and greater polarity; poorly detected and resolved by most GC-based methods
Examples of S-containing moieties that may be constituents of resin molecules	Moieties may include: Dimethylbenzothiophene and 2-Methyldibenzo-thiophene		Organic sulphur moieties such as these may contribute to total sulphur content of sour crude oils
Examples of O-containing moieties that may be constituents of resin molecules	Moieties may include:Benzofuran; Benzo[b]naphthofuran		Organic oxygen-containing groups in resins may be generated from PAHs by photooxidation or partial biodegradation
Examples of N-containing moieties that may be constituents of resin molecules	Moieties may include: Benz[a]acridine;Dibenzo[a,i]carbazole		N-containing groups contribute to polarity of the resins fraction

Figure 10. Main categories of resins in petroleum products and their properties, source Lee et al., 2016, p. 58.

Finally, in relation to asphaltenes, Lee et al. (2016) state that these substances are of different sizes and have different chemical properties depending on their composition. Thus, managing them is a complex and difficult task.

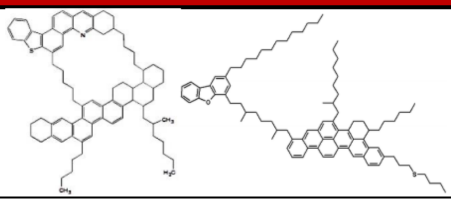
Name of chemical class or fraction	Example of class or fraction	Structure of example compound(s)	Properties and relevance of class or fraction
	Hypothetical asphaltene molecules, after Hoff and Dettman (2012) and Boek et al. (2010)		Numerous models of asphaltene structures have been proposed of different size, aromaticity and degree of condensation; different subclasses of asphaltenes with different chemical properties have been proposed recently

Figure 11. Main categories of asphaltenes in petroleum products and their properties, source Lee et al., 2016, p. 59.

Chapter 2

Deep-sea oil releases and their impact

In this second chapter of the paper, the interest is focused on the impact of the pollution of the ocean and the seabed from oil releases on the marine environment, that is, the animals and plants that exist at the area, as well as on ecosystems in general and human life. The main focus of the analysis is how the appearance of oil spills and hydrocarbon leaks in the marine environment led to problems in the chemical balance of water, water quality, the composition of the subsoil and the attractiveness of a destination. It is established, based on the analysis, that in the case of oil spills, in addition to the direct and observable consequence of the loss of life, there are other consequences such as the loss of income for people who exploit marine resources as well as permanent changes in the ecosystems that lead, in the long term, to serious health problems for animals and humans.

2.1. Marine environment

The protection of the ecosystem and the natural environment is a priority of the institutions in the European Union. A key reason that managing pollution and overseeing the processes of transportation, distribution, refining and exploitation of natural resources is important, is the fact that hydrocarbon platforms and facilities are located close to land. An accident, therefore, directly affects the populations of the states near the platforms and the biodiversity (Purser & Thomsen, 2012).

According to WWF (2018), available research shows that the contamination of seabed and sea waters is a major challenge for biodiversity and the environment. The 2018 report states that there is a significant biological risk from the contamination of waters from the transport of cargo by ships, from accidents that take place in the maritime space as well as from the extraction processes of natural resources and hydrocarbons.

According to National Wildlife Restoration (2014), an extremely typical example of the impact of accidents and incidents taking place in marine areas is that of the Deepwater Horizon which led to a dramatic decline in the dolphin population in the area and a dramatic decline in migration of sea turtles, which are already on the verge of extinction. Over five hundred (500) sea turtles migrated between 2011-2013 and species such as mahi-mahi fish and tuna were equally affected.

A typical characteristic of a potential effect of oil releases is the covering of birds' feathers with oil and the consumption of toxic substances from fish, which, in this way, the toxic substances are consumed by humans. Toxic consumption leads to DNA damage, carcinogenesis, and gastrointestinal, skin and respiratory health problems (Galil & Herut, 2011).

Figure 12. A brown pelican coated in oil struggles on East Grand Terre Island, Louisiana, on June 4, 2010 (AP Image)

To a significant extent, the contamination of the aquatic environment and the bottom comes from the use of crude oil and its by-products. Also, an important role in increasing water pollution levels is played by oil spills, the majority of which are smaller than 7 tons. These accidents contribute to water pollution to a much greater extent than major accidents, due to their frequency and the fact that they heavily contaminate small areas and have the potential to completely destroy an area (Ivshina et al., 2015).

2.2. Ecosystems

For ecosystems, the process of oil extraction and exploitation of the seabed and its resources is an important process with many ramifications. Ecosystems are maintained in a precarious balance, and thus a change in the chemical/physical composition of water, air and soil can upset this balance. As a result, species of plants and animals are lost and the process of evolution is achieved which, of course, would take millions of years to take place (International Ocean Discovery Programme, 2013).

Beyond the more obvious environmental disaster effects, such as mass fish and seabird kills, oil spills on the seabed and water pollution can have less visible consequences on the natural environment. One such example is the disruption of the natural balance as well as the destruction of bacteria and fungi that help maintain biodiversity (Lofthus et al., 2020).

Figure 13. A dead bird covered in oil from the Deepwater Horizon oil spill in the Gulf of Mexico, East Grand Terre Island, Louisiana, June 2010 (AP Image)

An example of a region that faces numerous problems due to water pollution/pollution due to accidents or intentional anthropogenic actions is that of Southeast Asia and the Indian Ocean. According to WWF (2018), regarding biodiversity, it is reported that oil and gas leaks in the area cause massive environmental impact leading to simultaneous loss of marine life, a reduction in biodiversity as well as destruction of the natural environment of the seabed.

2.3. Human life

In the 21st century, dealing with water and seabed pollution has become one of humanity's most important challenges. This problem turns out to be particularly important both because of the increase in human activity at sea and, additionally, due to the improvement of technologies for detecting oil spills and contamination, the problems created by the existence of contamination and leaks are becoming more noticeable. at the bottom (WWF, 2018).

Similarly, based on the research of Alrodini (2015), oil spills pose a significant risk to both humans and fauna/flora as, in many cases, they irreparably damage a local ecosystem. For instance, the Exxon Valdez accident led to the death of a huge amount of marine wildlife, even faced the threat of extinction, and the cleanup activities eliminate bacterial populations that could be beneficial for the bioremediation of the oil spill. At the same time, the challenge of their management lies in the high cost and the difficulty of assessing or even understanding the situation.

For humans, the contamination of water and the natural environment due to accidents and other anthropogenic actions (intentional or not) that lead to contamination has multifaceted negative consequences. These are both short-term and long-term. The immediately visible consequence is the costs of cleaning the waters, the loss of income for people who use marine resources for food and the impact on tourism. Using the example of Exxon Valdez, 26.000 jobs on the tourism industry were affected and there was a huge financial loss for the fishing companies. The immediate consequences are the long-term impact of oil spills on fauna and flora, biodiversity, and human health (Ivshina et al., 2015).

According to Yalaoui-Guellal, et al. (2020), organic water pollutants are a major problem for human health. The reason is that they contaminate the water, which may or may not be potable, and which are consumed by the species that, in turn, are consumed by humans. Also, the oil spill on the seabed changes the air quality and causes problems in the respiratory system. Therefore, there are observable direct and indirect consequences in human health and life, as presented in Figure 14.

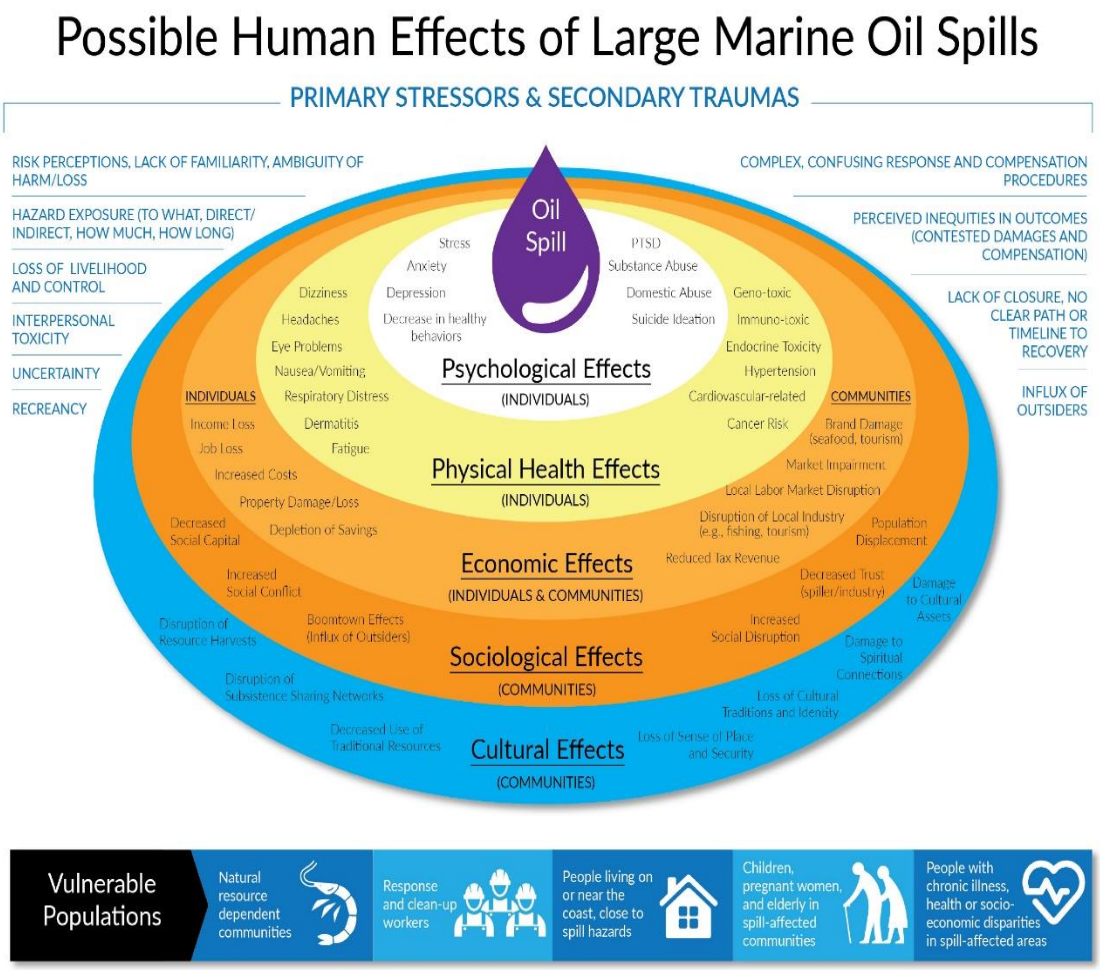


Figure 14. A summary of human effects research findings from studies on nine large oil spills (Oceanography, vol 34, 2021)

Also, in the available research, reference is made to a different category of impacts from such disasters during refining or disasters in areas at sea. For example, a storm in the North Sea region in 1980 resulted in the loss of one hundred and twenty-three (123) lives, while an accident at the Newfoundland refinery in 1982 resulted in the loss of all eighty-four (84) platform workers. Also, in the Deepwater Horizon platform accident in 2010, eleven (11) people lost their lives. Then, in 2013, the sinking of a rig belonging to the Saudi Aramco company resulted in the loss of three (3) lives (Harris et al., 2016).

Figure 15. Deepwater Horizon oil rig fire (AP Image)

Chapter 3

Targeting oil spills

In the third, this chapter, the focus is on how to deal with phenomena related to the management of accidents and mistakes as well as natural disasters that led to the creation of an oil spill and/or the contamination of the seabed. The aim of the chapter is to examine the different options available to those in charge in order to manage the facts of the situation as well as to immediately limit the impact of the situation. In particular, reference is made to methods such as bioremediation, the use of dispersants, mechanical processes and simulations. Then, reference is made to possible challenges associated with the effective treatment of oil spills and the contamination of the seabed and subsoil, directly limiting the environmental impact of similar events and their economic impact.

3.1. Natural Recovery

The simplest method of dealing with the oil spill cleanup operation is to make use of the unpredictable actions of nature like the sun, the wind, the weather, tides, or naturally occurring microbes. It is used in certain cases when the shoreline is too remote or inaccessible, or the environmental impact of cleaning up a spill could potentially far outweigh the benefits.

Lofthus et al. (2020) state that, during and after the existence of an accident leading to the occurrence of an oil spill, physical, chemical, and biological changes take place in the environment. However, it is also reported that oil has specific chemical properties, and, through the weathering processes, such as the evaporation, the dissolution and the photo-oxidation, which are acting together, the impact of an oil spill can be greatly reduced because it is dealt with naturally through chemical and biological processes.

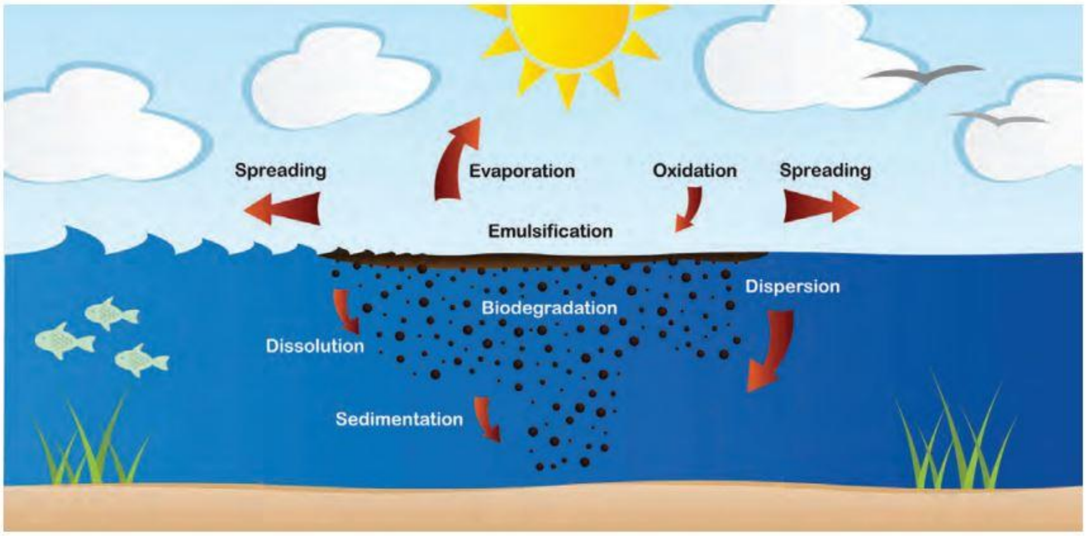


Figure 16. Weathering processes acting on oil at sea. Once oil strands on the shoreline some of these processes will no longer apply (ITOPF, 2018)

Due to the constancy of these elements, the oil generally evaporates or is broken down into simpler components. It is one of the most cost-effective methods, but on the other hand, it is a highly time consuming and unreliable process and thus needs constant and close monitoring. It should not be confused with 'sitting down and doing nothing'.

A crucial factor in cleaning up an oil spill is the location where it has happened. Most of the oil spills take place far out in the sea, so they are generally left to naturally decompose in the environment. As they get closer to the shores, the treatment gradually begins.

The treatments follow a general rule: (All distances measured from the shoreline)

- 200 nautical miles and beyond – No treatment is used, unless the case is very severe.
- Between 20 and 200 nautical miles, booms and skimmers may be used.
- Between 20 and 10 nautical miles, dispersants are used.
- For areas very close to the shoreline, biological agents are used.

These are only general rules and can be altered based on the type of oil that has been spilt and the prevailing weather conditions. No two oil spill cases are the same, so each one is evaluated individually based on its own characteristics (Marine Insight, 2021).

3.2. Bioremediation

In relation to bioremediation, the US National Response Team, NRT, (2000) states that this technology is an option for cleaning and reducing marine pollution. As a technology, it is neither the first choice of the competent bodies, nor an immediate solution. Instead, it requires time, resources, and expertise. The process is one of the actions followed in the gradual transition to a new seabed regeneration system after the remains of an accident have first been removed.

The process of bioremediation concerns the decomposition of hydrocarbons in a way that is engineered and using natural methods. These natural methods involve the use of bacteria and fungi that feed on petroleum products/by-products and then metabolize them. As a result, new chemical elements are produced, and the site is cleaned with the least possible burden on the natural environment of a specific area (Alrodini, 2015).

Bioremediation is a technology that is still used to help authorities identify a problem and in-situ (on-site) deal with an emergency. The biodegradation of petroleum products and by-products is of particular importance in the metabolism, recycling, collection or reproduction of hydrocarbons and its derivatives. This is done by applying methods of introducing bacteria that consume the products / by-products of the oil. However, how bioremediation will be done depends on the depth since anaerobic bacteria respond more to great depths than aerobic ones. This is due to the absence of oxygen at the bottom (NRT, 2000).

In the same vein, Yalaoui-Guellal et al. (2020) state that the ideal solution is the use of biological water purification methods. The proposed method is the use of microbes and biosurfactants which are alternatives to chemical surfactants and environment friendly due to their biodegradability, biocompatibility, and lack of toxicity. These microbes are selected based on their diversity and their properties in water purification. According to Chen (2018), two basic approaches are followed during bioremediation - biostimulation and bioaugmentation.

During the biostimulation process, the growth of native microbial oil receptors is stimulated by the addition of nutrients or other restrictive substrates, and/or by changes in environmental conditions (e.g., surf-washing, addition of oxygen from plant growth, etc.). During the bioaugmentation process, oil-degrading bacteria are added to replenish the microbial population that existed in an area before the event that caused a change in the microbial/chemical balance of the water. Sometimes, bacteria that don't exist in the area are added to the native population because of their ability to degrade oil more efficiently.

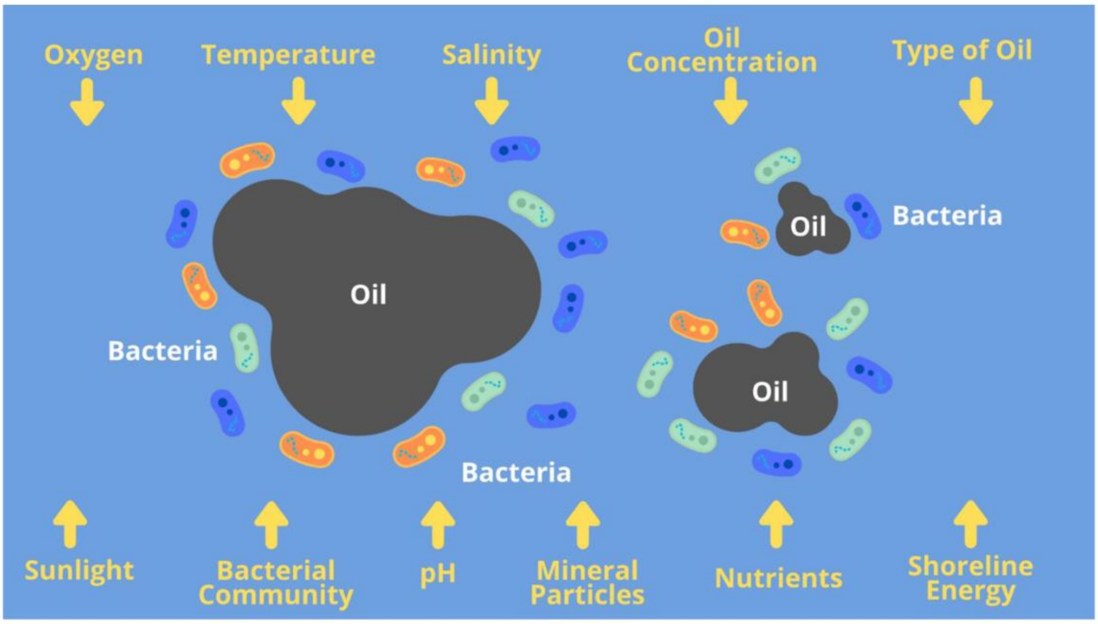


Figure 17. Factors affecting the biodegradation of oil by bacteria in seawater, Bacosa et al. (2022)

A wide range of marine bacteria can degrade oil components, but a single organism is limited to the number of the components that can metabolize. For a complete biodegradation of oil, a synergy of different bacterial species is needed. A few potential factors that affect the development of oil degrading communities in oil polluted marine sediments are temperature, oxygen level, depth, water chemistry, and initial community. A few examples of marine microflora species are the bacterium *Alcanivorax borkumensis*, the *Rhodococcus erythropolis* and the *Pseudomonas stutzeri*. These bacteria have been identified from the isolation and chemical analysis of water samples in areas with the presence of hydrocarbons (Alrodini, 2015). A more comprehensive list of bacterial species and their degradation profile can be found at Figure 16.

Oil-Degrading Bacteria.	Hydrocarbon Specificity
Alcaligenes aquatilis BU33N	Crude oil and phenanthrene
Alcanivorax sp. IO_7	Alkane
Alcanivorax sp. 24	Alkanes
Cupriavidus metallidurans CH34	Toluene
Cycloclasticus sp. strain BG-2	Phenanthrene
Cycloclasticus sp. 78-ME	Polycyclic aromatic hydrocarbons
Cycloclasticus sp. strain P1	Naphthalene, phenanthrene, pyrene
Halomonas sp. strain MCTG39a	Hexadecane
Halomonas pacifica strain Cnaph3	Naphthalene
Marinobacter hydrocarbonoclasticus SdK644	Crude oil
Oleispira antarctica RB-8	Aliphatic alkanes
Pseudomonas aeruginosa N6P6	Phenanthrene and pyrene
Pseudomonas pseudoalcaligenes NP103	Phenanthrene and pyrene
Pseudomonas sp. sp48	Phenol, naphtalene, pentadecane
Pseudomonas aeruginosa GOM1	Hexadecane
Ralstonia pickettii	Crude oil

Figure 18. An overview of oil degrading bacteria isolated from different marine ecosystems and their hydrocarbon specificity, Dell' Anno et al. (2021)

Henry, Netzer, Davies & Brakstad (2020) mention in their research the process of biotransformation of oil compound groups. This process is the result of the reaction of algae with metal atoms that takes place at an average temperature of 13 degrees Celsius. According to the data of this research, while it was expected that n-alkanes would break down in Oil-Related Aggregates (ORAs), a complex reaction took place in both seawater and ORAs. From their experiment it follows that the biotransformation of the oil compound groups for all the samples that contained oil presented a specific biodegradation process which depended on both the water temperature and the sum of the Gas Chromatography/Mass Spectrometry (GC-MS) analyses.

For the case/alternative of biodegradation it is noted by Abou Khalil et al. (2021) that, in certain locations, certain bacteria and microorganisms naturally exist that consume oil and gas deposits that are naturally placed on the surface of the water. It is noted as well, that n bodies of water such as salt lakes, certain microbes survive the placement of large amounts of oil and, if a certain threshold is exceeded, then the toxicity increases to such a great extent that equilibrium cannot naturally occur. For example, when there is a toxic spill then there can be a death of the micro-organisms that would normally contribute to reducing the toxicity of the water.

3.3. Dispersants

According to Alrodini (2015), in the early stages of a spill, small amounts of oil are removed by natural methods such as, for example, through natural processes. These processes include geothermal reactions as well as the dissolution of oil in a large volume of water. This results in the area ceasing to exhibit high toxicity. An important role can also be played by the natural presence of bacteria in the area that feed on hydrocarbon derivatives.

According to the report by Maung-Douglass et al. (2019), the use of dispersants can contribute decisively to reducing the contact of oil droplets/spills and its by-products with living organisms on the seabed. The process of using these is described in the diagram below:

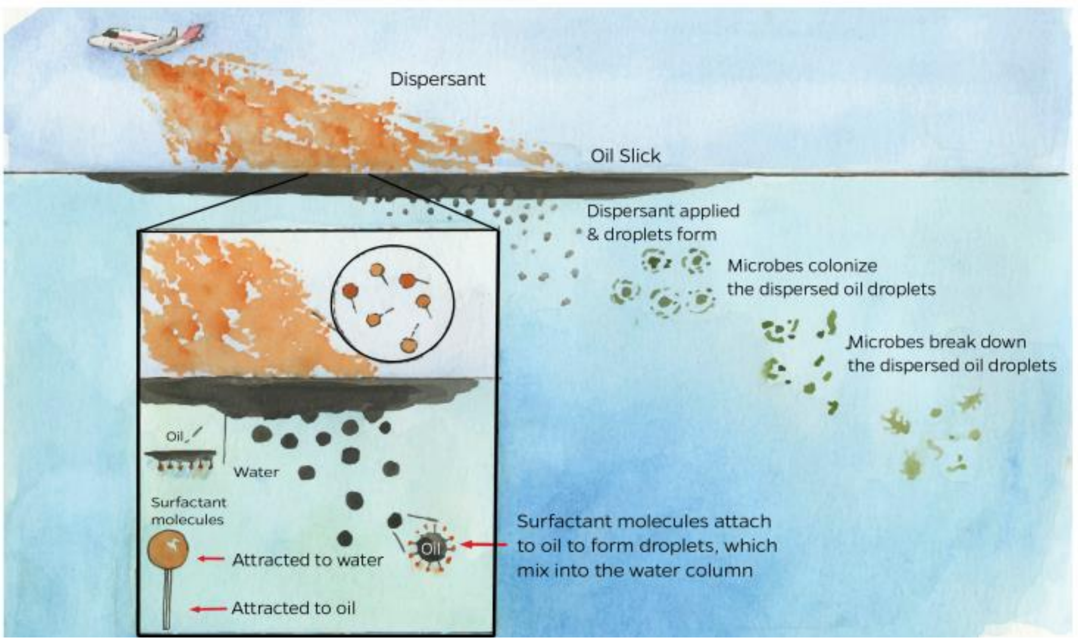


Figure 19. Use of dispersants in tackling oil spills, source Maung-Dauglass et al., 2019, p. 2

As can be seen in the Figure 17, the dispersants are dispersed by aerial means towards the spot. Then, the microbes colonized the oil droplets that are dispersed and dissolve them. Depending on their chemical composition, dispersants work in a different way to attract oil and either use evaporation, or other chemical and physical processes and, therefore, it is a complex technique that requires appropriate preparation and research. As mentioned, not all techniques are suitable for all environments, so it is important to study the characteristics of an area, the type of accident and weather conditions before choosing one technique over another (Maung-Douglass et al, 2019).

Alternatively, the use of dispersants may also involve the utilization of nanotechnology. Nanotechnology is used to select substances in minute quantities that will be used with appropriately engineered techniques to clean water from oil. Substances such as carbon nanotubes absorb oils and repel water. As such, they act as huge sponges for absorbing toxic substances and petroleum by-products from seawater. These technologies are specialized and particularly useful for cleaning the seabed (Maung-Douglass et al., 2017)

Although the use of dispersants has many benefits as it contributes to the relatively immediate and timely intervention at the site of an accident, the use of dispersants without proper planning and in the wrong amount can have negative consequences for the environment and people. For example, Corexit 9500A has been shown, in large quantities and with prolonged use, to lead to dermatological and respiratory problems. Also, Corexit 9527A can cause liver and kidney problems if taken orally and cause gastrointestinal problems. It can also cause problems in the nervous system and/or have significant side effects from prolonged exposure to these chemicals (Graham et al., 2016).

Additionally, for dispersants, it can be noted that they are not usable in any incident. For instance, in the case of ice, it can be particularly difficult to approach the space below the surface. Above the surface, burning can take place if the water is non-saline, however, if it is salty or if the ice is particularly bulky it is very likely that dispersants cannot be used. Dispersants, also, may not be particularly useful in case the weather conditions are unsuitable. Based on the example of the Arctic, Brandvik et al. (2007) states that, if the temperature is extremely low, then due to the high viscosity, the effectiveness of the dispersants decreases. This leads to the conclusion that, while dispersants are useful in managing the situation, they are not a panacea.

3.4. Mechanical processes

Based, then, on the research of Walther (2014), a technology used in cleaning the sea and water volumes, especially if the spill is located near the coast, is the "flooding and flushing" technique. Using this, low-pressure water is pumped through to "push" the spill ashore and then clean it up at a lower cost and risk. This technique is particularly useful if not a long time has passed since the incident or if the conditions are suitable to collect the oil that has accumulated on the surface of the water.

Wilson et al. (2019) have compared the available technical means in investigating and managing oil spills. These technologies are summarized below:

According to Wilson et al. (2019), the use of saildrones can have many benefits in long-term data collection and is suitable when a robust medium that has satellite-based digital tracking technologies is required. This medium is suitable for harsh weather environments but is not suitable for sampling and cannot be recovered if damaged very easily. Also, if it ends up in the sea, it does not decompose naturally.

Then, in relation to drifters, this technology is used when GPS tracking is required but, like saildrones, it is not easy to recover if it ends up in the sea and they are non-biodegradable. Drones, then, are unmanned means of intervention and can use many sensors. Their main advantage is flexibility, but the disadvantage is that they rely on a battery of limited duration and that they are not useful in difficult environmental conditions (Wilson et al., 2019).

Unmanned Surface Vehicles	Advantages	Disadvantages
Saildrones	• Long range and duration for data collection of up to 12 months • Fast — travel up to 10 knots (11.5 mph) • Durable — sturdy, long-lasting, and reusable • Collect high quality data in real-time • Can endure rough weather conditions • Wind and solar powered, no use for batteries • Can include many sensors	• Cannot sample water at depth • Require specialist to operate
Drifters	• Come in many different sizes, allowing deployment from multiple locations • Contain GPS units to track position	• Difficult to recover after deployment • If not biodegradable, can pollute the ocean environment • Must deploy many at a time
Unmanned Aerial Vehicles	**Advantages**	**Disadvantages**
Drones	• Can be equipped with many sensors • Come in many sizes	• Strict limits on where and how they can be flown • Duration limited by battery power • Sensors compact due to limited space • Cannot operate in windy conditions • Difficult to operate at night
Blimps and Balloons	• Observe changes over long periods of time from various altitudes • Can be equipped with many sensors • Free of vibration, which is better for images	• Height of flight limited by length of cable and flight path restrictions • Use helium to stay inflated so occasionally need to be brought down and refilled

Figure 20. Technologies and means of managing and investigating oil spills, source Wilson et al., 2019, p. 7.

For cleaning the bottom when a quantity of oil has been deposited in the mud, there are different possible and tested techniques that have proven utility in the event of an accident. These solutions, based on data from the European Commission (2015, p. 74):

→ the separation of the mud resulting from the sedimentation of hazardous toxic waste with the liquid and solid materials found at the bottom using shale shakers and similar technologies,

→ the preparation for a similar accident with the use of chemicals or other materials that are placed protectively and for preventive roles on the seabed in order not to find the situation out of control if an accident occurs,

→ the use of closed loop-solids control systems that are used to pass the sludge through the equipment that the management company has and to clean the sludge from material deposits,

→ the use of mechanical means to separate waste from non-waste,

→ the use of thermal treatment to separate the hydrocarbons from the residues created/found after the accident in the area.

3.5. Simulations

According to the CSB's Guide to Major Accident Prevention at Oil and Gas Refining Sites (2020), investing in taking appropriate measures to prevent accidents and disasters in areas and sites where such projects take place is essential. The reason is that with proper planning, disasters that cause loss of human and animal lives, changes in the environment and environmental pollution are avoided. To do this, investing the necessary means as well as capital in research, technology and engineering action planning is necessary.

For oil spills, it is important to evaluate the different alternatives available to the agencies and, accordingly, study the advantages and disadvantages of each alternative and the cost-benefit ratio of each of them. The selection of these will be made according to the data available to the responsible engineers and researchers who have been assigned the task of optimizing the situation as well as the availability of the different technologies. Also, an important role is played by whether the weather conditions are suitable, whether real-time intervention can be done and whether the technologies available have proven utility in a specific case (Ivshina et al., 2015).

Different technologies and practices can be applied to determine the best strategy to deal with the occurrence of an oil spill. Which technologies to choose depends on the location, the size of the spill, the expectations of the operators, the severity of the accident and the availability of more immediate or less invasive solutions. Also, an important role is played by which agency makes decisions as different solutions are applied in the territories of a specific state and different in the international seabed (Ivshina et al., 2015).

According to Ivshina et al. (2015), over time, the way in which a similar crisis is dealt with can start from prevention or the conditions that prevailed in an area before the creation of the spill. Of central importance are three (3) different dimensions:

- the understanding of the chemical properties of oil,

- the change in conditions prevailing in an area,

- the effectiveness of one technology over another.

Simulations can also be particularly useful in cases where, in the absence of data, it is not known which of the possible solutions will be more effective in a particular accident or event. One such possible example of leveraging the technologies of biology, biochemistry, engineering, and informatics is the sampling of fungal DNA-RNA to analyze how they might be used in different environments to break down hydrocarbon elements and restore the physical/chemical balance (Velez, Gasca-Pineda & Riquelme, 2020).

Another aspect that is of great importance for prognosis and early preparation which has been shown to be required to avoid tragic accidents or problems related to difficulties is managing them before and not when they occur. For this reason, accident statistics are useful in relation to incident metrics, size, and severity. In this way, the effects of a crisis can be assessed as well as simulations can be made and the best possible solution can be chosen (Adams & Socolofsky, 2004. According to Adams & Socolofsky (2004, p. 2), on average their characteristics are as follows:

Variable	**Units**	**Magnitude**
Water depth, H	m	844
Orifice diameter, D	m	0.12
Volume release rate of oil, Q_o	m^3/hr	60
Volume release rate of gas, Q_g	Sm^3/s	0.6
Density of oil, ρ	g/cm^3	0.85
Viscosity of oil (diesel, crude), μ	g/cm/s	0.04, 0.8
Oil-water surface tension, σ	g/s^2	25
Large oil droplet slip velocity, w_{so}	cm/s	14
Gas bubble slip velocity, w_{sg}	cm/s	30

Figure 21. Statistics of oil spills, source Adams & Socolofsky, 2004, p. 2

Adams & Socolofsky (2004) report that simulations are also useful in monitoring and supervising the positions of refineries and platforms. With the use of digital media and technologies, scientists can measure the frequency of measurements using sounders and, thus, examine whether their operation is normal. Also, they can calculate whether or not there is damage and the possibility of causing an accident as well as the concentration of toxic substances near the platform or area of oil drilling / oil reserves.

An important role is also played by the fact that, when an activity is generally carried out on the seabed, whether it concerns a research or construction activity, or the response to a crisis, it is necessary to respect certain minimum conditions for the protection of the seabed environment. The studies and actions that must take place concern, among many, the study of the soil and bedrock data of the seabed as well as the study of the properties of the surface and seabed water. An area's atmospheric data and seismicity, ecology and biodiversity are also required to be considered. Oceanography is a science that can allow a better understanding of the data for a region and the seabed in general (European Commission, 2015).

Also, a challenge that is noted in the case of drilling for the exploitation of hydrocarbons as well as, consequently, in the case of causing a crisis, is the fact that many areas are protected and/or have special cultural significance. For example, in many countries there are underwater archaeological sites as well as tangible and intangible cultural heritage sites. So, it will be the task/responsibility of organizations that are not only technical to manage the challenge of exploiting natural resources in a region (European Commission, 2015).

3.6. Technical challenges regarding deep sea oil pollution management

3.6.1. Weather conditions

A particularly important challenge accompanying the protection of the seabed from oil spill pollution is the fact that, unlike soil contamination, on the seabed, the oil spills do not remain stable. Water currents carry the spill from one area to another while, in over 10% of cases, wind currents carry and disperse the spill. Other important physical factors are atmospheric conditions, such as air temperature, rainfall and air density, while an important criterion is whether the waters are shallow or not (Ivshina et al., 2015).

3.6.2. High pressure and water density

A serious obstacle to the removal of oil spills is also mentioned in the research of Chen (2018) and concerns the depth factor. At great depths such as that of the Deepwater Horizon example, which was about 1.5 km, the water pressure is so great that floating collection methods and human approach are not feasible. Therefore, a possible choice in high pressure areas are dispersants which are agents that are practically used together with biological agents to break up the films created by oil spills and oil collection into both slicks and droplets.

Also, it is found that the process of building the facilities becomes particularly costly and difficult because the materials are often porous, particularly heavy and suffer gradual damage over time due to water pressure. Gradually, the weight of the water is expected to create operational problems for the oil pumping facilities with possible negative results for the environment and the facility itself. The risk, therefore, increases as depth increases (BP, 2011).

3.6.3. Visibility

An environmental challenge that can arise in the open sea is low visibility, both if there is fog and in the winter months in the Arctic circle. In this case, the use of dispersants is useful as it becomes possible to deal with the situation without the question of approaching with mechanical means. However, the challenge of using boats and other means to solve the problem in the region remains (WWF, 2007).

3.6.4. Biodiversity

The seabed environment is, in any case, complex. In the depths of the oceans, the density of the water is increased, and the visibility is low since sunlight does not reach it. Also, there is a great dependence of approachability on weather conditions while, often, there is megafauna in the area. The existence of megafauna such as whales makes the task even more difficult, both because it is not desired to disturb their natural environment and because these species are protected and must be protected. These species are migratory, however, if an accident occurs at a certain time, then it is highly likely that the species will not be able to travel their "paths" and change habitat as predicted based on their life cycle (Fisher, Montagna & Sutton, 2016).

Another challenge that occurs is that the greater the biodiversity in an area, the more likely it is that specialized measures to deal with pollution are required. For example, in areas with many species of plants, marine species and birds, the technologies required to approach the area of the spill, to clean the water and restore natural healing are likely to be both more complex and more costly. These conditions are considered from the very first stages of implementing a strategy (EMSA, 2013).

The measurement of nutrients in the seabed is of great importance for choosing the optimal biodegradation process of petroleum pollutants as well as, in general, of hydrocarbons. Certain naturally occurring nutrients in the seabed limit the possibility of successful water purification using biological agents. Such examples are the existence of inorganic nitrates (NO_3), phosphate compounds (PO_4^{3-}) and iron that limit the rate of biodegradation (Chen, 2018, p. 17).

Accordingly, the rate of biological degradation of the seabed after water contamination can be reduced if there are either too many or too few chemical elements in the seabed. Research shows that the most effective natural ingredients used for biodegradation are fertilizers. However, as tools, they can delay the process of natural oil absorption if the study is not complete or the density of water and its content of inorganic and organic compounds have not been sufficiently estimated (Chen, 2018).

3.6.5. Temperature

Temperature, however, can make it faster or slower to resolve a problem caused by toxic waste or oil contamination. Pollutants are soluble and are also food for microorganisms. The lower the temperature, the higher the viscosity of the oil. Therefore, the less likely it is to biodegrade immediately. The higher the temperature, increases the rate of enzymatic activities of the microbial community, and as a result increased biodegradation processes will be and the faster the restoration of the natural balance. Ideally, water temperatures close to 15-20 degrees Celsius have the highest degradation rates, and help to quickly restore the physical, chemical, and biological balance (Chen, 2018).

3.6.6. Winds

According to EMSA (2013) statistics, a particularly significant technical challenge in dealing with seabed or surface contamination is the fact that environmental conditions can dramatically reduce the ability of agencies to manage a situation. Important criteria that determine the extent to which management is feasible are water composition, currents, temperature and type of winds, factors that are corelated as, when temperatures are extremely low, strong currents and winds can occur simultaneously and make an operation even harder.

Additionally, in areas with strong winds, according to WWF (2007), access by manpower or boats containing the appropriate equipment to remove the spill may be difficult. The high-intensity winds make it difficult to monitor the course of the contamination from the air or to intervene on the spot. Mechanical recovery in this case can be done by ships dropping anchor at the spot. However, burning is not possible due to the conditions that will prevail. Likewise, dispersants cannot be used.

Chapter 4

The effects of bioremediation from oil spills.

Then, in this fourth chapter of the work, reference is made to a tangible example, that of the Deepwater Horizon accident in the Gulf of Mexico. This accident, which took place in 2010 and occurred at a depth of 1500 meters, is one of the most serious events observed in relation to deep water oil spills. The contamination caused significant problems such as mass deaths of species, migration of marine species, displacement of the slick and the appearance of oil droplets even 16,000 meters from the accident site, as well as serious problems in tourism. The effects of this crisis are expected to be long-term and the way in which the challenge was managed constitutes an example to be avoided for future similar accidents. On the other hand, this accident is also a lesson for humanity and the academic community about the importance of environmental protection as well as the application of the best possible methods in the construction, maintenance and management of floating refining platforms, refineries and drilling sites.

4.1. The Deepwater Horizon Incident

A typical example of such accidents is the Deepwater Horizon spill in the Gulf of Mexico which caused significant problems in the bordering states. The Deepwater Horizon accident was a disaster that occurred on April 20, 2010, and, today, is perceived as a dual problem with many stages of development (Eude, Napoli & Guarnieri, 2016; White, et al., 2016). These problems have been tackled in different ways, combining water and seabed cleaning technologies as well as non-conventional oil residue isolation methods (White, et al., 2016).

According to Eude, Napoli & Guarnieri (2016), this accident was the first deep subsea blowout in the history of the oil and gas extraction sector and was a crisis that was faced by many countries and caused problems in just as many states of the world. The accident, in the first stages of its development, caused a crisis in the marine environment and the biodiversity of the Gulf of Mexico and, in the second, it was a serious issue for those in charge as the cleaning of the seabed was a technological and engineering problem of high complexity and seriousness.

The timeline of the accident is as follows (Eude, Napoli & Guarnieri, 2016):

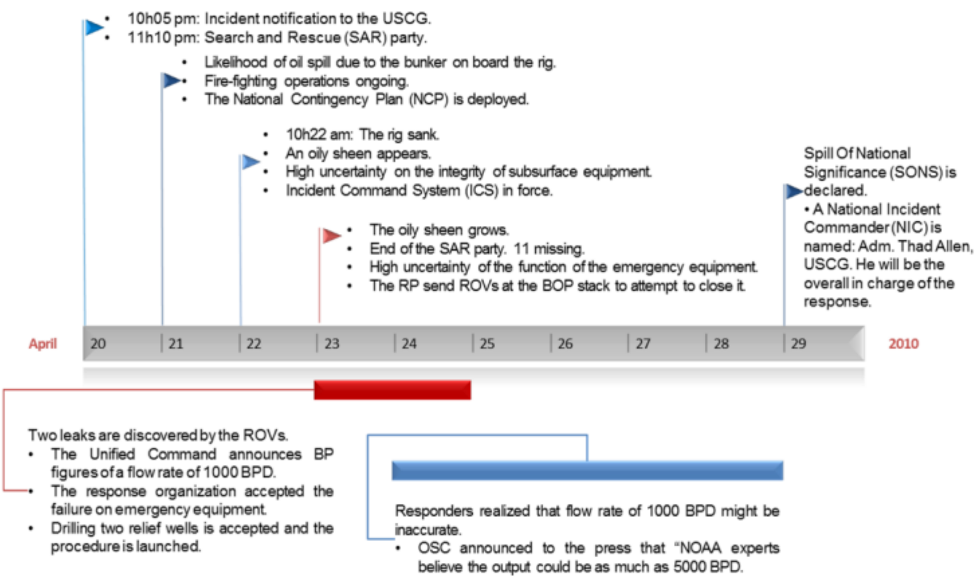


Figure 22. Deepwater Horizon - analysis of events, citation: Eude, Napoli & Guarnieri, 2016, p. 777.

According to the analysis of Eude, Napoli & Guarnieri (2016), two main leaks were reported, the first was identified by the Unified Command which announced a leak of size 1000 bpd and, the second, a flow of up to 5000 bpd. After the initial announcement of the accident, on April 23, 2010, it was announced that the pollution levels and the size of the spill had increased to high levels and, on April 29, 2010, a specialized response from the US side was foreseen.

Based on research by Passow & Stout (2020), this accident was so severe that the duration of efforts to seal the rift lasted eighty-seven (87) days. This accident was so serious that it contaminated water samples as far as 155 km away from the site of the incident. Regarding the accident, it is noted that 2-20% of the oil that leaked from the well was deposited on the bottom, which means that the ecosystem of the Gulf of Mexico was permanently affected. The spill was 10 cm thick while its footprint was at least 6.5 sq km.

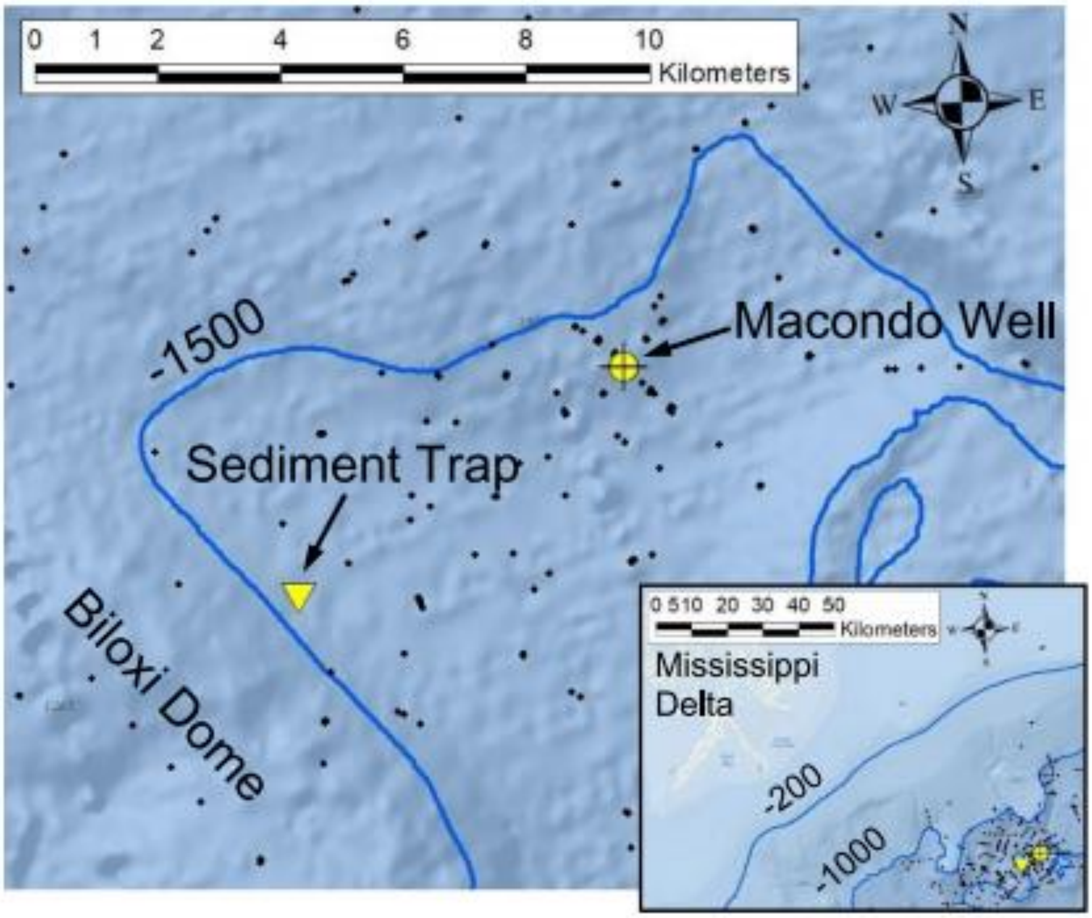


Figure 23. Analysis of the map of the Deepwater Horizon accident, source: Passow & Stout, 2020, p. 2.

The competent committee of BP reports that, in the Deepwater Horizon accident, the disaster that occurred was complex because the entire system that was implemented was also complex. The basic effects and the difficulty of managing the accident were typical of the problems caused at a subsea refinery. The reason is that, in this oil well, people were working who were ignorant of the possible risks that would cause a disaster in the installation as well as the financial interests served by the operation of Deepwater

Horizon. The disaster led to the deregulation of BP, a serious problem in the company's reputation as well as significant problems in the supply of energy to areas covered by the company's oil and gas energy imports. Also, tourism in the Gulf of Mexico region was significantly affected and, in fact, in the long term due to the fact that the incident received a lot of publicity (BP, 2011).

In addition to an important challenge for the management of the accident when it occurs at great, especially, sea depth, the water pressure turns out to be a challenge for the very construction and maintenance of the oil and natural gas extraction facilities. The water pressure is so great that the materials are transformed before refining while, many times, petroleum by-products such as tar rise to the surface of the water near the refining site. This poses a permanent and particularly serious issue for managers to manage (BP, 2011).

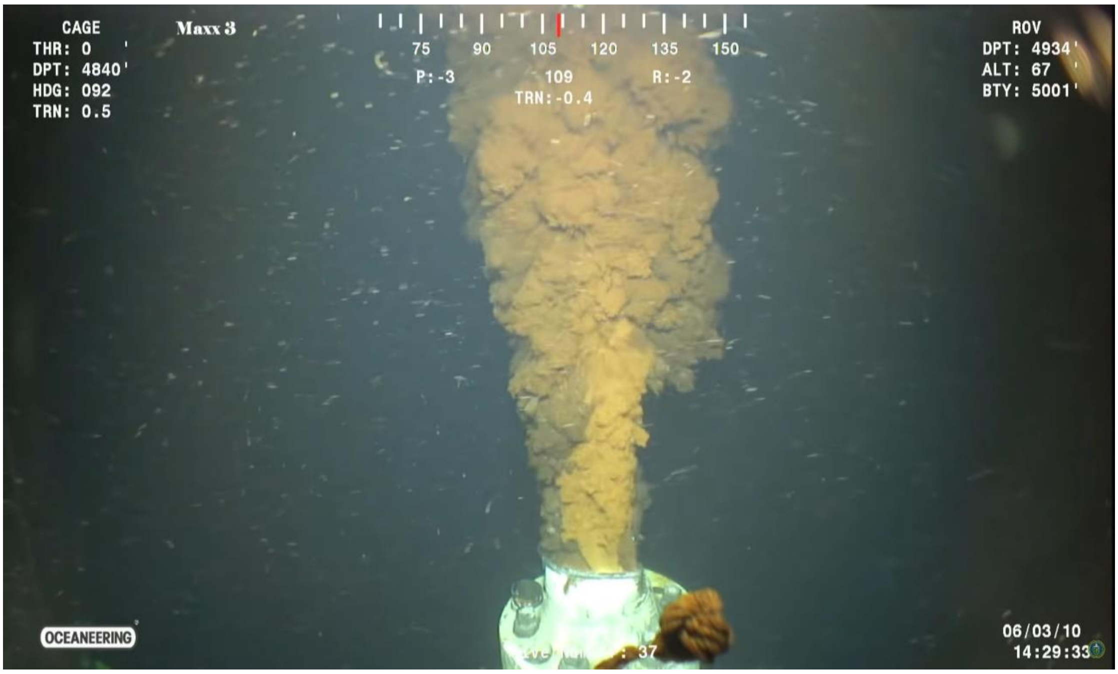


Figure 24. Macondo well blowout (AP Image)

The example of Deepwater Horizon is also a typical example of an accident with a large impact on the environment. According to BP's (2011) report, this incident constitutes the largest ecological disaster the USA has ever faced. This disaster has led to increased temperatures, water quality impacts, deforestation and the deaths of vulnerable sperm whale populations in the Gulf of Mexico. The effect of this disaster was also significant in entire regions of the USA such as the state of Louisiana.

4.2. Challenges

In the research of Passow & Stout (2020), it is also mentioned that one of the important reasons for not cleaning the waters was the fact that, due to the depth of the failure, photo-oxidation was not possible as well as the gradual natural cleaning that occurred, finally, after a period of almost thirteen (13) months and after additional extensive efforts by the authorities. Later research based on the study of zooplankton secretions on the seabed showed that there are still oil residues and toxic waste on the seabed to this day.

The application of laboratory tests played an important role in the process of dealing with the accident that caused the Deepwater Horizon spill in Mexico. The laboratory tests used in this case included, among other things, the location of the oil spill, the analysis of the chemical characteristics of the sea water sample as well as the laboratory study of water purification methods. This process showed that there are new perspectives and technologies for water disinfection/remediation in case of oil spills (White, et al, 2016).

Another major challenge faced by authorities and experts is the fact that approximately 90% of the water volume in the Gulf of Mexico is at depths that are difficult to clean or reach by conventional means. This volume is contained in depths over 200 meters for over 9/10 of the waters of the Gulf of Mexico. Another 20% is located at depths of around 3000 meters, points that are particularly difficult to reach in general. The difficulty of cleaning the water has led to the oil and its by-products "leaving" the food chain, which has led to great loss of animal life in the area as well as problems in the quality and safety of human life even 14 km away, from where the accident took place (Fisher, Montagna & Sutton, 2016).

At the ocean floor in general, sampling, accurately counting and collecting qualitative and quantitative data, and acquiring images is a particularly complex challenge. For this reason, the difficulty of managing an accident that takes place in deep water is significantly greater than those that take place in shallow water or on land. In the case of deep-sea accidents, the areas to be accessed are often inaccessible, without natural light and without the possibility of being approached by conventional audio-visual means (Fisher, Montagna & Sutton, 2016).

In addition, among the most important challenges involved in the construction of refining / pumping facilities, especially in relation to cementing procedures, it follows from the example of Deepwater Horizon that a special design is required so that the cement acts as the main barrier that protects against leakage oil. The risk factors based on BP's report (2011, p. 118) are:

(1) the challenges of the drilling process itself, especially in the area where cement is placed,

(2) the difficulty in managing the highwater pressure,

(3) the problems related to water circulation,

(4) the limited number of centralizers,

(5) the low flow of cement and,

(6) the small volume of cement as a material.

An important, parallel issue raised in the case of Deepwater Horizon was that, while there was legislative initiative to develop mechanisms to deal with the crisis and there was relevant experience due to the hundreds of offshore deep water oil drilling facilities, the response was a challenge for the authorities. In areas that do not belong to the full jurisdiction of a state, indeed, while exploitation and maintenance are attributed as a responsibility and as an obligation to the organization that undertakes the refining and transportation, a possible accident does not cause only limited effects (Hansson, 2013).

An important reason that this accident was not prevented and developed into a crisis for the USA and neighboring states, was the fact that the technicians and researchers in the field had overestimated the strengths of the cement. Cement, as a material, is very reliable and is used in seabed and underwater constructions. However, the pressure at the drilling site was at 1250 psi and, despite the initial simulations, the pressure increased to such an extent that the cement lining was not sufficient to limit the risk of damage to the drilling site (Board & National Research Council, 2012).

On the contrary, as it emerged from the whole analysis, because the effects of such a disaster are long-lasting and, at the same time, management becomes difficult since the spill can be transferred to other areas, proper coordination is required. This coordination can be a matter of national importance especially when it involves, in addition to the state in which the company installing the platform is based, one or more neighboring states (Hansson, 2013).

4.3. Effects of bioremediation

The incident of DWH is a particularly typical case of the influence of individual biological and other factors during the presentation of an oil spill incident. For this reason, the incident is extensively studied as a case study in the global literature, given that the extent, duration, and form that the incident took, had a long-term impact on the underwater and coastal environment of the Gulf of Mexico, as well as the economic activity in SE USA, northern Mexico, and northern Caribbean islands.

The restoration of the area requires a combination of natural processes of the biological factors of the ecological environment of the area, and technical interventions to remove the harmful elements. A key element for the restoration of an area affected by an oil spill is bioremediation. Specifically, the natural processes of microorganisms remove basic organic factors, changing them into chemical compounds with less impact on the environment.

Prior to the DWH spill, there was relatively little information about the marine microorganisms that degrade hydrocarbons in the Gulf of Mexio, as well as the effect of hydrocarbons on them. The extensive research that was made after the incident, revealed microbial communities that were working together at the center of bioremediation services with highly adaptive and complex dynamics. Also, these studies established new methods for assessing and monitoring the ecosystem health, new discoveries were made and new tools invented to build a strong foundation to help the scientific community to prepare better to respond to future environmental catastrophes (Weiman S. et al., (2021).

In the research of Bôto, et. al., (2021), bioremediation is examined in terms of its impact on the DWH and SE Spain oil spill. According to the researchers, the process of bioremediation in the individual chemical elements of oil, which consists of more than 17,000 hydrocarbons, causes their reduction to hydrocarbon derivatives, which can then be reduced to non-harmful organic compounds. As Bôto, et. al., (2021) report, the appearance of the phenomenon depends on a set of factors, the main ones being:

- From the type of oil that causes the oil spill.
- The geographical location of the oil spill.
- The size of the oil spill.
- The weather and climate conditions, depending on the period of development of the oil spill.
- The origin of the oil spill and the degree of ease - difficulty of restoring the infrastructure that caused it.

All the above parameters affect the growth of microorganisms that cause the degradation of the chemical elements that make up the oil spill. The assistance of bioremediation, according to the data of the researchers, ensures the rapid restoration of the area, and the prevention of contamination with dangerous derivatives in the ecological environment. The researchers examined the phenomenon through chemical analysis of oil spill samples from Spain and the Gulf of Mexico.

The method followed by the researchers, during the conduct of their experiment, is the study of the rDNA samples of the microorganisms in the sample, in order to identify the factors that cause the growth, reproduction, and effect of the microorganisms in the oil spill, during the bioremediation process. The researchers then conducted Predictive Functional Profiling in order to isolate the factors that confer these properties and proceeded to the statistical analysis of the data.

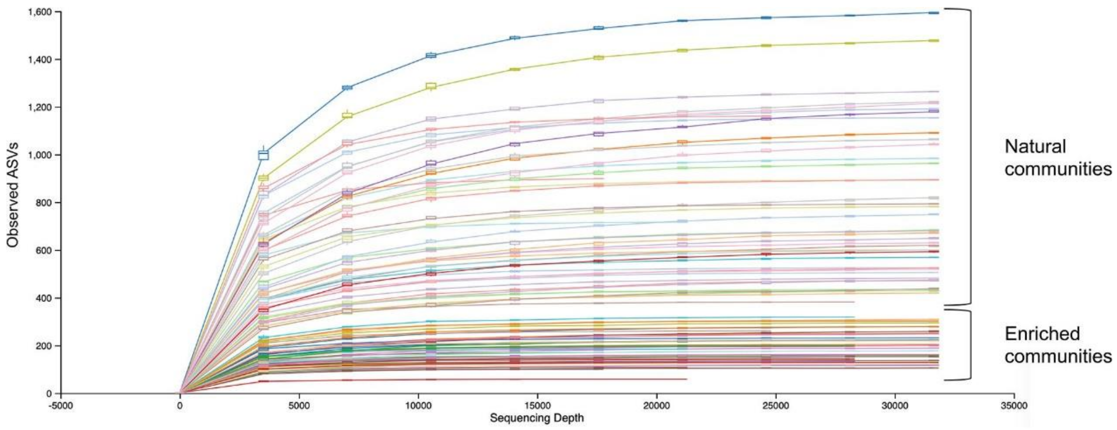


Figure 25. Analysis results of bioremediation effects on oil spills, (Bôto, et. al., 2021)

As can be seen from the diagram above, the differentiation between natural and enriched agents of the bioremediation process concerns the consistency with which the microorganisms consume chemical agents, and as a result they confirm the research hypothesis that the enhancement of the process confers benefits on the removal process of the oil spill.

Accordingly in the research of Weiman, et. al., (2021), applying similar experimental methods to a sample exclusively from the DWH case, yielded similar results. Specifically, the researchers studied the speed of occurrence of the bioremediation process, in relation to weather and climate conditions. As in the case of the previous research, so in the current one the researchers concluded that bioremediation accelerates the process of dealing with the oil spill and limits the environmental risk. At the same time, however, the researchers noticed that the climatic conditions of the Gulf of Mexico played a crucial role in the presentation of the bioremediation process through the natural mechanisms of the microorganisms.

As the researchers report, studying the collected samples concluded that the increased water temperature, in contrast to the case of Spain, where the phenomenon took place in the Atlantic Ocean region, caused the acceleration of the reproduction of microorganisms, and consequently the mitigation of effects of the oil spill. Similarly, in the research of Panchal, et. al. (2018) and Pete, et. al. (2021), which were conducted with similar experimental methods, concluded that climatic conditions play a role both in the speed of completion of chemical processes and in their outcome. Examining samples from regions with different climatic conditions, the researchers concluded that in colder climates the process is completed at a lower speed, but the potential for the development of dangerous derivatives is reduced, while the opposite is true in warmer regions.

4.4. Tackling the crisis

These technologies that have been applied and used in tackling the crisis caused by the Deepwater Horizon accident were, among many (White, et al., 2016).:

→ the aerial detection of oil spills through the search of the accident site.

→ the digital localization of the spots through the use of internet technologies.

→ the use of passive sensors and other instruments to detect the spot on the surface and the subsurface of the water.

→ chemical tests with on-site sampling.

In detail, Eude, Napoli & Guarnieri (2016), describe the problem solving process followed for the case of the Deepwater Horizon accident as follows: (1) the problem was identified, (2) the research, technical and practical problems of crisis, (3) the best engineering approach was chosen, (4) the cofferdam was used as a coping method, (5) the Riser Insertion Tube Tool (RITT) was used, (6) the CDP (Containment and Disposal Project) process was followed, (7) the Top Hat 4 process was used, and, (8) a 3-ram capping stack was constructed. In more detail:

(1) In the problem statement stage, the situational data, the depth and pressure of the accident and its exact location relative to the US coast were considered. The depth was 1500 meters, the pressure was 150 bar, there was no natural light or human access, and the site was such that it was only a short distance from the US coast and at a site that is particularly sensitive in relation to the natural environment and life at the bottom.

(2) Regarding the research approach and the choice of the research method that would be used to find an optimal solution, no hydrostatic pressure study was done but an

extraordinary control on the surface and the bottom with a focus on the best cleaning practices.

(3) In relation to the mechanistic approach taken, officials proposed both short-term and long-term solutions to coordinate policies and make a management plan if the first solution fails.

(4) Indeed, the first possible solution considered is the cofferdam. A cofferdam is a collection system based on pumping oil from the site of the disaster using a steel container that is placed over the site. It was chosen because it had proven benefits in disasters such as Hurricanes Katrina and Rita. The logic of using the cofferdam is ideal for shallow water but it did not work at the depth of 1500 meters.

(5) RITT was then selected. This system was evaluated during the period 8 to 25 May 2010. As a solution it is based on using a 21-inch diameter pipe to collect as much oil as possible with a limit of 12000 bpd. Over 10 days, 22,000 bpd were collected from a RITT. The other two systems installed to extract the oil were unsuccessful.

(6) CPD was then implemented, a project of great funding and scope aimed at the gradual recovery and return of the seabed to its initial stages. The plan followed was implemented between June 16 and July 14, leading to a cleanup of 20,000 bpd of oil from the seabed.

(7) In the next stage, Top Hat 4 was implemented. Top Hat 4 was a response plan with different stages and procedures and between June 3 and June 26, it collected approximately 500,000 bbd.

(8) The 3-ram capping stack was the only device that was designed to seal the well and cut the flow. On July 15th, the capping stack sealed the well, followed by 2 days of integrity tests and monitoring to ensure that no loss is achieved. Combined, the use of the above means significantly reduced the environmental impact of the accident.

Conclusions

This work aimed at the critical analysis of the parameters that lead to the pollution of the sea, especially the seabed, both from human errors and accidents, as well as due to human activities concerning, in particular, the extraction, refining and transportation of oil. Based on the research, it has been shown that pollution is becoming increasingly higher and more challenging for the planet and humanity. Climate and deep-sea pollution are two interrelated factors that cause loss of lives and income, particularly in developing areas of the world.

This dissertation, having considered all the above, aims to contribute to the available literature through the critical investigation of the factors that lead to sea pollution and their effects, as well as through the investigation of the possible / available techniques that exist for cleaning the seabed and removing oil residues. Its main impact is, therefore, the fact that it is a critical discussion of a plethora of academic sources in order to highlight best practices and tried techniques that contribute to the minimization of risk of deep-sea pollution in the future.

According to what was critically studied in the first chapter of the study, it is found that the pollutants of the seabed are numerous, and the pollution does not come mainly because of the accidents or random events that take place but, much more, because of the regular contamination that takes place due to human activity. The contamination of the environment from the spill of heavy metals and toxic substances, fuel and garbage are much greater in severity and extent than is the burden from large-scale events such as the Deepwater Horizon accident.

Natural factors and changes in the ecosystem caused by pollutants are also of great importance. When humans pollute the seabed, populations of micro-organisms that feed on pollutants as well as organisms that are more resistant to pollution often increase. Large mammals and animals that maintain the balance in an area also migrate from heavily polluted areas. Hence, a development that would take place over time suddenly occurs leading to disequilibrium.

In the second, then, chapter of the study, the results of the pollution of the seabed were analyzed. It turned out that, for the marine environment, the consequences are numerous and particularly important, including the mass death of animals and plants as well as causing a lack of balance, which was mentioned above. The impact on ecosystems is correspondingly large. So, the impact on humans is just as great. Indeed, air, water and soil pollution have direct health consequences such as disease and indirect ones such as DNA alterations and mutations and cancer.

For this reason, it is examined, in the third chapter, how the issues related to the pollution and contamination of the seabed can be managed. The first solution mentioned is bioremediation, a process of utilizing biological agents to solve the pollution problem. Microbes and fungi consume the oil by-products and metabolize them and, therefore, the natural cleaning of the seabed occurs. This process is time-consuming and complex but effective in a very large number of cases.

Then, the use of dispersants is also useful. Based on the available literature, the use of these is suitable especially for small damages and quite friendly for the environment. However, it may show limited effectiveness in cases where environmental conditions are not suitable such as in the Arctic and North Sea where temperatures are particularly low.

The mechanical methods are then analyzed with an emphasis on the techniques that can be applied per type of event. It is found that, as in the case of bioremediation and the use of dispersants, there are limitations depending on weather phenomena and environmental conditions. Overall, in all cases, the most important problems reported were related to bottom visibility, site accessibility and the ability to clean the bottom without excessive spillage of oil to adjacent sites.

Then, in the fourth chapter and with an emphasis on the Deepwater Horizon example, a real event that constituted a major environmental disaster is examined. This disaster was, to a large extent, difficult to contain due to the fact that the depth was very great, the volume of oil found was exceptionally large and the material (cement) placed at the bottom did not react as expected and cracked.

When accidents followed by oil release occur offshore, the main goal is to prevent the oil from affecting the coastal ecosystems both ecologically and financially. The initial prevention actions may include physical blocking of oil spill, using floats, barriers, or booms. Oil spills are also chemically disrupted with the use of dispersants, which create smaller droplets of oil for easier dispersion in water. In the Deepwater Horizon accident, dispersants were used on the surface waters and by injection of dispersants was applied at the well-head at the bottom of the sea. Another action could be the controlled burning of the oil on the site of the spill.

Oil can disintegrate into carbon dioxide and water naturally in marine environments by bacterial communities. These microorganisms exist in the area even before an oil spill and they are distributed throughout the water column. The response of these bacteria after the Deepwater Horizon accident was to rapidly increase their population, consumed tons of oil and enhanced the remediation of the area. In deep sea and in areas with extremely low temperatures the biodegradation of oil might occur with slower rates. In any case, bioremedation of hydrocarbons may prove advantageous after an oil spill.

However, the immediate response of the bacteria of the northern Gulf of Mexico to the DWH oil spill could be due to the extensive hydrocarbon seepage and extraction activities that happen there, making this observation to be under question and possibly not applicable to other offshore locations.

In every aspect of prevention and rapid emergency response, studies shall be conducted in every place with offshore activities, especially in deep-sea waters, that little of the ecosystem is known. This preparation could help the scientific community to understand and, in case of an accident, provide valuable insights, for enhancing the bioremediation process of the specific area.

These studies shall focus on the different characteristics of each location, like temperature, oxygen, initial bacterial community, nutrients, type of oil and other crucial factors that could affect the rates of bioremediation process and reduce in time the environmental impact of such an oil spill.

Overall, the research established the fact that, although the exploitation of oil and hydrocarbons, in general, is particularly important, the prediction and simulation of possible accidents is required so that accidents similar to the Deepwater Horizon do not occur in the future.

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