University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Masters in Environmental Monitoring and Nature Management in the Northern Oil and Gas Producing Regions	Spring, 2018 Open
Writer: Kaia Hodne	(Writer's signature)

Faculty supervisor:
Daniela M. Pampanin

External supervisor(s):
Hans Petter Lohne (IRIS)
Øystein Arild (IRIS)

Title of thesis:

Quantification of Effect of Oil Spill Response Systems

Credits (ECTS): 30

Keywords: Oil spill response Arctic Environmental risk analysis Effectiveness model	Pages: 78 +enclosure: 5 Stavanger, April 15th, 2018

Quantification of Effect of Oil Spill Response Systems

Kaia Hodne

University of Stavanger

Master's Thesis

University of Stavanger
Environmental Monitoring and Nature Management in the Northern Oil and Gas Producing Regions
Faculty of Science and Technology

Stavanger, June 2018

Abstract

The purpose of this thesis is to develop models to determine the effectiveness of oil spill response systems in Arctic environment and to evaluate their impact on the ecosystems. Three response systems are investigated: mechanical recovery, *in situ* burning, and chemical dispersion. With the increase in petroleum activities in the Arctic, it is important that companies gain the knowledge needed to exploit the resources in a sustainable manner. What works well in one place will not necessarily have the same effectiveness in other places. This is precisely why it is important to understand the factors that determines the effectiveness of the response and the degree of environmental impact in the Arctic. The thesis includes a case study of a simulated oil spill from the Johan Castberg field, located in the Barents Sea. The developed models are used to determine the potential volumetric reduction of an oil slick. The application of the models in a case study helps to point out the main factors affecting the effectiveness of the response systems in the Arctic. Among all the identified factors, response time, wind and water-in-oil emulsion rate seem to be the determining factors. Oil slick thickness is identified as the major source of uncertainty in the existing models. Based on the expected response time and the oil properties of the studied oil types in the Arctic, mechanical recovery seems like the best response option.

Acknowledgements

I would like to express my great appreciation to my supervisors at IRIS, Hans Petter Lohne and Øystein Arild, as well as my supervisor at the University of Stavanager, Daniela M. Pampanin. They have all provided me with valuable suggestions and constructive discussions while being patient and encouraging. My gratitude also extents to Eric Patrick Ford at IRIS for his contributions. Sincerely thanks to my sister, Stina Hodne, who spent long hours revising my thesis.

I would also like to express my gratitude to NOFO, Statoil and Akvaplan-Niva for their contributions and permission for reproduction of their material.

Finally, I would like to thank my family, friends and fellow students for their support during times of frustration and all the great moments throughout these two years in the Master Programme. This achievement would not have been possible without them.

Content

List of figures

List of tables

Terminology and abbreviations

BAOAC	Bonn Agreement Oil Appearance Code
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
DSHA	Defined Situation of Hazard and Accident
DWH	Deepwater Horizon
EBSP	Estimated Burn System Potential
ERA	Environmental Risk Analysis
ERSP	Estimated Recovery System Potential
MIRA	Method for Environmental Risk Analysis
MIZ	Marginal Ice Zone
MRDB	Marine Resource Data Base
NCA	Norwegian Coastal Association
NCS	Norwegian Continental Shelf
NEBA	Net Environmental Benefit Analysis
NINA	Norwegian Institute for Nature Research
NOFO	Norwegian Clean Seas Association for Operating Companies
NOROG	Norwegian Oil and Gas
PAH	Polyaromatic Hydrocarbon
SIMA	Spill Impact Mitigation Assessment
VEC	Valued Environmental Components
VOC	Volatile Organic Compounds

A_{boom}	Area of boom system (m^2)
A_{spill}	Area of spill (m^2)
B	Burn rate for a specific oil (mm/min)
C_{max}	Maximum capacity of the boom system (m^3)
D	Draft length/length of the boom skirt (m)
ER	Encounter rate (m^3/min)
h	Oil slick thickness (mm)
L	Length of the boom (m)
NC	Number of cycles possible during an *in situ* burning operation
OR	Oil recovered by the skimmer system (m^3)
PE	Percentage of emulsion/water content (%)
RR	Recovery rate (m^3/min)
S	Swath width (m)
t_{burn}	Time required to burn the volume of max capacity (min)
TE	Throughput efficiency of oil/emulsion of skimmer (%)
t_{max}	Time required to fill the boom to max capacity (min)
t_{offset}	Time required to offset the system a given safety distance (min)
$t_{operation}$	The operation time of the system (min)
$t_{residue}$	Time required to collect burn residue (min)
v	Towing speed of the system (m/s)
V_b	Volume of oil burned (m^3)
V_i	Initial oil slick volume before a response (m^3)
V_{oil}	Volume of oil without any water (m^3)
V_r	Residual oil slick volume after a response (m^3)

1. Introduction

1.1 Background

In 2008 the U.S. Geological Survey (USGS) conducted a Circum-Arctic Resource Appraisal (CARA) to evaluate the potential for petroleum resources in the area north of the Arctic Circle (66.56° north latitude). Total mean undiscovered conventional oil and gas resources in the Arctic were estimated to be approximately 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids [1]. Companies therefore wished to expand their operations to these areas in the search for more resources. With the increased interest, it became apparent that more research was needed to understand this new territory. It is important that the resources are exploited in an environmentally responsible way, especially when moving into remote and undisturbed areas with lack of information and knowledge.

There is always an environmental risk related to petroleum activities. The risk increases concurrently with the vulnerability of the ecosystems. The Arctic is an environment comprised of sensitive ecosystems with rare and economically valuable species. Therefore, an environmental risk analysis (ERA) must be conducted to be aware of the potential harm that an oil spill may cause. In the event of an acute oil spill, a response method will be implemented. Which method to use depends on a variety of factors, such as the type of oil, environmental conditions, and the ecosystems located in the influence area. It is important that the potential impact on the ecosystems from the response is also considered.

1.2 Purpose of this thesis

As part of the project “A transatlantic innovation arena for sustainable development in the Arctic (CoArc)”, the International Research Institute of Stavanger (IRIS) leads one of the work packages on risk management. Part of the work package is to develop a framework to assess the risk related to petroleum activity in the Arctic and the impact on the ecosystems. The aim of the project is to develop future-oriented and cost-effective solutions to environmental monitoring and risk assessment for the oil and gas industry as they move into Arctic waters. The project receives funding from the Ministry of Foreign Affairs, as it is in accordance with the criteria of the grant scheme “Arktis 2030”.

In this thesis, models to assess the effectiveness of response systems are developed and their impacts on the ecosystems are evaluated. The purpose of the developed models is to calculate the volumetric decrease of an oil slick in order to determine and compare the effectiveness of the most commonly used response systems. The ecosystem perspective must also be considered, as one method may be more effective from the volumetric perspective, but not as favourable from an ecosystem perspective. In this thesis, different perspectives, such as oil volume removed, ecosystem vulnerability, environmental limitations, logistics and cost, are compared and discussed in relation to their importance in the Arctic.

1.3 Objectives

In order to determine the effect of an oil spill response system, several perspectives must be considered. The main objective in this thesis is to:

"Create quantitative models to assess the effectiveness of oil spill response systems."

Some sub-objectives should also be answered:

- identify ecosystems in the Arctic and their vulnerability,
- assess the impact of response systems on the Arctic ecosystems,
- identify the uncertainties with existing effectiveness models,

1.4 Structure

Chapter 2 contains the theory that is used to develop the effectiveness models and to conduct an environmental evaluation of the oil spill response systems. In chapter 3, the methodology and the different steps in the evaluation are described, while in chapter 4 the effectiveness models for the different oil spill response systems are derived. The developed models are further used in a case study on the Johan Castberg field in the Barents Sea to compare the difference in the reduction of the oil slick volume for various implemented response systems. The models and the various response methods are then discussed from various perspectives (e.g. effectiveness, environmental impact, cost, requirement). The limitations related to this thesis are discussed in chapter 5, while the conclusion, knowledge gaps and recommendations for future research are presented in chapter 6.

1.5 Area of interest

This thesis focuses on the sea areas defined by the Norwegian Government as the Barents Sea-Lofoten management plan area. The boundary of the area is presented in Figure 1.1. The area stretches up along the Norwegian coast from Lofoten and the Norwegian Sea in the south to the Arctic Ocean above Svalbard in the north, from the Greenland Sea in the west to the Barents Sea in the east [2]. The management plan covers a wide area where the environment varies greatly; from the coast and the shallow continental shelf to the Arctic Ocean at depths more than 4000 m below sea level, and from areas in the harsh Arctic waters with ice-covered oceans, to milder areas with warmer water from the Atlantic Ocean.

Figure 1.1 The Barents Sea-Lofoten management plan area [2].

The Barents Sea was opened for oil and gas activities in 1979 and the first exploration well was drilled the following year, in 1980. Only one year later hydrocarbons were discovered in the Askeladden field, which today is included in the Snøhvit field. Still, it was not until 2007 that the production finally started. It was by then the first producing field in the Barents Sea-Lofoten management plan area. In 2000 a second field, named Goliat, was discovered about 50 km southeast of the Snøhvit field. To date these are the only two producing fields in the Barents Sea. However, a third field, Johan Castberg, was discovered in 2011 and is expected to start producing in 2022 [3].

2. Theory and literature study

This chapter will provide an overview of different oil spill response systems and their limitations in the Arctic, as well as the vulnerability of relevant ecosystems with the risk of being impacted by a potential oil spill.

2.1 Ecosystems in the Barents Sea-Lofoten management area

An ecosystem is according to the dictionary Encyclopædia Britannica defined as *"the complex of living organisms, their physical environment, and all their interrelationships in a particular unit of space"* [4]. Ecosystems in the Arctic are highly seasonal, varying with accessible sunlight, temperatures and ice formation. The Barents Sea-Lofoten management plan area can be divided into four ecosystems: the Barents Sea ecosystem, the Svalbard and Bjørnøya ecosystem, the coastal area ecosystem, and the deep-water ecosystem. Within each ecosystem, sensitive areas which are particularly valuable and vulnerable have been identified (Figure 2.1). This identification is based on scientific assessments of the biological production, biodiversity, and the area ecological function in organism life cycles, for instance spawning and breeding for fish and birds.

2.1.1 The Barents Sea ecosystem

The Barents Sea is a relatively shallow sea with an average depth of 230 meters. The input of warmer, nutrition rich water from the Atlantic Ocean causes a bloom in biological production. The Barents Sea ecosystem is characterised by short food chains, with many organisms depending on the same key species as food source. Key species are defined as organisms playing a fundamental role in the ecosystem [5]. Polar cod is considered a key species, as it is the main prey for many seabirds and marine mammals. Fish resources in the Barents Sea-Lofoten management plan area are of high economic value and an important industry for Norway. Herring, capelin, cod and haddock are among the species of highest demand, and they all spend part of or all their life in the Barents Sea [2].

Arctic species are robust and have adapted to the harsh climate, but the short food chains make them easily susceptible to changes. They are therefore regarded as very vulnerable in oil spill situations. Shorter food chains may also result in higher bioaccumulation rate of toxic

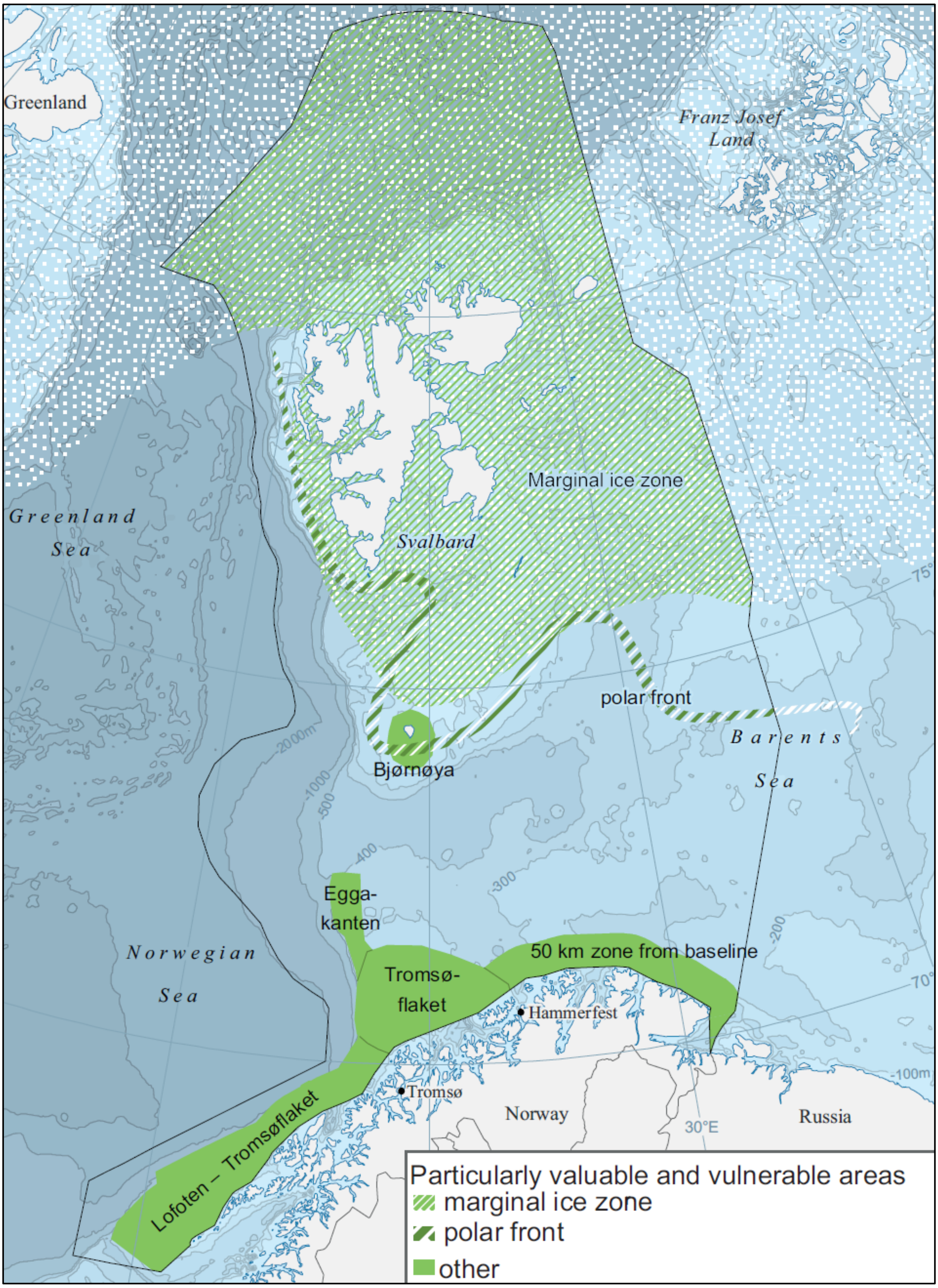


Figure 2.1 Particularly valuable and vulnerable areas in the Barents Sea-Lofoten management plan area [2].

compounds in top predators [5]. Two zones in the Barents Sea have therefore been delimitated as sensitive areas with high value and vulnerability: the ice edge and the polar front.

The polar front is an oceanographic front where warm Atlantic waters meet cold Arctic waters. The front is highly productive with rich planktonic algae blooms and a high biodiversity. The phytoplankton are grazed by zooplanktons which again provide food to fish, mammals and sea birds [2]. Both arctic and boreal species gather near the polar front. Such a high concentration of species makes the area highly vulnerable [6].

The ice edge, also called the marginal ice zone (MIZ), is the transition zone between ice and water. In this thesis, the MIZ is defined by a 10-30 % ice concentration based on the recommendations from the report on developing a Method for Environmental Risk Analysis (MIRA) adapted for the marginal ice zone [7]. The ice edge is an important area for species that depend on ice for part of or all their life. The biological production and diversity increases during spring and summer when the ice retreats northwards. A 20 to 50 km wide belt of phyto- and zooplankton forms along the edge. This attracts a diverse group of species, such as the fish polar cod and capelin, the little auk and Brünnich’s guillemot birds, polar bears and ringed seals [6]. The ice edge ecosystem differs from the polar front ecosystem due to the colder water. Lower sea temperature means fewer grazing zooplanktons. Instead, there is more benthic fauna to feed on the sinking biomaterial. As with the polar front, an oil spill near the ice edge will affect a large number of species [5].

2.1.2 The ecosystem around Svalbard and Bjørnøya

Svalbard consists of many islands, the main ones being Spitsbergen, Nordaustlandet, Edgeøya, Barentsøya and Prins Karls Forland. All activities around the island group are regulated by the Svalbard Environmental Protection Act and 87 % of the coast and territorial waters are protected as nature reserves and national parks [5]. Svalbard has a diverse fauna, both onshore, on the drift ice, and in the ocean. The ocean is the main food source for most of the wildlife, especially in the productive areas south and west of the island group. Svalbard is home to a great range of bird species and 18 of them are reported as part of the Red List species [8]. The Red List is a database which provide information on taxonomy, conservation status and distribution of endangered species [8]. The sea ice around the islands create important grounds for many mammals, such as the walrus, bearded seal, ringed seal, and polar bear. The last two are estimated to experience a 30 % population decline over the next three generations due to the shrinking sea ice [5].

Bjørnøya is located approximately halfway between Svalbard and the mainland. This small island is surrounded by the polar front in three directions. Bjørnøya and the surrounding territorial waters has, because of the ecological importance, been protected as a nature reserve [5]. During moulting season, many species gather here to shed their old feathers. This island is also a key area during the breeding season and is the only known breeding ground for the great northern diver. Some of Europe’s largest colonies of Brünnich’s guillemot and common guillemot can also be found here. Over a 10 years’ period, there has been detected a reduction of more than 80 % in the Norwegian population of common guillemot. The species is therefore listed as critical on the 2015 Norwegian Red List. The razorbill, another bird species commonly found on Bjørnøya during the breeding season, is listed as an endangered species, with a 50 to 80 % population decline over the last 10 years. Its breeding population is estimated to be as low as 100 couples in Norway, most of them on Bjørnøya [8].

2.1.3 The coastal area ecosystem

The Norwegian coast is known for its rich fish resources and highly productive waters. This attracts both humans and wildlife. Three zones have because of this been delimitated as vulnerable along the coast; the Lofoten area, Tromsøflaket, and the northern coast towards the Russian border.

The coastal area outside of Lofoten is, compared to the rest of the Norwegian coast, characterised by a narrow continental shelf. The currents are stronger in this area and bring warm water closer to the coast than other places. It is a key area for fish, used for spawning, maturation and overwintering. During the spawning season, the fish migrate down to Lofoten and makes it one of the most concentrated spawning grounds in the Arctic. Later, eggs and larvae drift with the current up along the Norwegian coast and eventually enter the Barents Sea. Due to the rich food sources, also marine mammals and sea birds concentrate here. Grey seals, harbour seals, harbour porpoises and killer whales are some of the marine mammals found along the coast. The many islands in the Lofoten area are important nesting and moulting spots for sea birds such as the Atlantic puffin, razorbill, common guillemot, black-legged kittiwake, and the European shag. Common eider, king eider, yellow-billed loon, black guillemot, and cormorants migrate to the islands for the winter [5]. Many of the mentioned bird species are either listed as vulnerable, endangered or critical in the 2015 Norwegian Red List [8].

Tromsøflaket is a 25,000 km^2 area located of Finnmark, at the entrance to the Barents Sea. The depth of the flake varies from 114 m in the southwest area to 350 m in the north. The flake was formed during the ice age, and the geology is mainly glacial moraine. On the seabed there are seagrass meadows, kelp beds and sponge colonies. The sponge colonies are of great ecological importance for fish and other marine organisms and work as habitat for bacterial communities [9]. The sea bed topography creates eddy currents which increase the residence time of the water over the flake. Eggs and larvae drifting from the spawning areas in the south towards the Barents Sea therefore tend to concentrate here for some time before moving on with the currents. The longer residence time increase the possible exposure time to oil in case of a spill [6].

Sponge colonies inhabit the coast all the way towards the Russian border. As with the rest of the Norwegian coast, also this part has high biological production and a diverse fauna. A high concentration of fish attracts predators higher up in the food chain. Among them are seabirds, which search for food up to 100 km out from the coast. They use the northern fjords for moulting and overwintering. Steller's eider is the world's rarest diving duck and as much as 5 to 10 % of its population migrate to the Varangerfjord for the winter. Marine mammals such as the grey seal, harbour seal, harbour porpoise and killer whale can also be found up here [5].

2.1.4 The deep-water ecosystem in the Norwegian Sea

The Eggakanten area is the geological edge of the Norwegian continental shelf (NCS), starting at 200 m depth and leading down to about 750 m depth. In these deeper areas one can find deep-water fish, among them the piscivorous Greenland halibut. The slope continuous down into the deep waters of the Norwegian Sea until it levels out between 2000 and 2500 m depth. The shelf edge is visible all the way from the North Sea to north of Svalbard, and the area recognised as Eggakanten is the edge west of Tromsøflaket. The Eggakanten area receives nutrition rich waters from the Atlantic Ocean and has therefore a high biological production. However, the biodiversity declines with the depth. At 600 to 700 m depth, there is a water transition zone between the warmer water and deep, colder water. The cold water keeps a constant temperature below 0 °C [9]. In the shallower parts there is a rich fauna of small crustaceans, several types of coral reefs and sponge communities. Among them there is the rare *Radicipes spiralis,* also called the pigtail coral. In Norway, it can only be found north on the Eggakanten area [6]. The Røst Reef, situated along the edge, is the world's largest deep-water coral reef known to date. Coral reefs are preferred habitats for many organisms, and so far, 600 species have been identified in the Eggakanten ecosystem [5].

2.2 Assessing the ecosystem vulnerability

2.2.1 Definition of vulnerability

According to the governmental management plan, vulnerability can be defined as "*a measure of how liable a species or habitat is to be negatively affected by external, often anthropogenic pressures"* [10].

Species vulnerability can be determined based on survival and reproduction of an individual or a species population. Vulnerability may vary depending on the time of the season, the stage of life cycle, and the distribution. Both fish and birds are more vulnerable during the spawning and breeding season, when large parts of the populations gather in concentrated areas. Most organisms are also more vulnerable in the early stages of the life cycle, such as eggs and larvae. Vulnerability of habitat depends on type of species, whether the host is sessile or motile and if it can escape from pollution. It also depends on the habitat-forming species. Corals and sponges are slow-forming and are therefore particularly vulnerable [10]. When performing an ERA, vulnerability of populations, communities and ecosystems are the most important factors. Unfortunately, these are also the most difficult to measure.

2.2.2 Method for Environmental Risk Analysis (MIRA)

Environmental risk in an oil spill situation can be defined as a combination of the possibility for an oil spill to occur and the associated consequences. The MIRA method is developed by the Norwegian Oil and Gas (NOROG) and operators on the NCS. The objective of the cooperation was to create a common framework for performing ERA related to acute oil spills. Since the first report was published in 1999, it has been revised multiple times and the latest edition was published in 2007. It is the standard ERA method applied by operators on the NCS.

The method is based on the use of oil drift simulations and species and habitat vulnerability values to predict the expected population loss. As it is impossible to analyse all organisms and environmental compartments, some species and habitats that are defined as valued environmental components (VECs) are identified and studied. Any species that are part of the Red List are automatically considered a VEC [11]. To predict the impact on a population, e.g. fish, seabirds or marine mammals, the expected restitution time required for the population to be restored to its original size is estimated. While for habitats, e.g. different types of shorelines, it is the time required to recover the biodiversity that is estimated. Data on vulnerability is retrieved from various databases, such as The Marine Resource Data Base (MRDB), Norwegian Institute for Nature Research (NINA) and Seapop [7]. The results are presented as a percentage of the risk acceptance criteria, decided by the operators [12].

A VEC populations vulnerability towards oil is in the MIRA described using a grading system ranging from low to high vulnerability. The grading system is based on both individual species vulnerability and population vulnerability. The vulnerability of an individual is determined by studying e.g. the species residence time in the influence area and its utilisation of the area, its behaviour, physical fitness, and recovery capabilities, whereas the vulnerability of an entire population is determined based on e.g. the population size, flocking tendencies, age distribution, and reproductive potential [11].

2.2.3 Vulnerability towards oil

It is often said that the Arctic species are more vulnerable and sensitive to anthropogenic pollution due to their unique biochemical and physiological adaptations. Arctic species often have a lower metabolic rate, which can result in delayed toxic effects, and a larger lipid content that may increase the potential for bioaccumulation [13]. However, recent studies argue that they are no more sensitive to oil pollution than species living in temperate areas. More research is needed before the same can be said on a population level [14, 15].

The consequences of an oil spill (e.g. toxicity and lethality) vary among the different species, depending on their biology, physiology and behaviour. Arctic seabirds and some marine mammals are dependent on their feathers and fur as insulation to survive the harsh and cold climate. When coated in oil, the insulating capacity is reduced, which quickly leads to hypothermia, or their natural buoyance may be lost, leading to drowning. Loss of insulating capacity is especially harmful in the Arctic climate. Birds and mammals exploiting the water surface are at the highest risk. Further down in the water column the concentrations rarely stay high long enough to cause any acute toxic effects. Most fish species have adapted to the occurrence of hydrocarbons by exposure through natural oil seepages from the ocean floor and can readily metabolize the compounds. However, the economic value of the fish is often lowered due to reduced quality as food. This is a major problem, as the Arctic is an important source for the fishing industry [16]. Organisms in water depths greater than 10 m are rarely affected by an oil spill, unless the oil starts to sink and sediment [17]. Sinking and sedimentation of oil is not very common, but certain conditions increase the possibility as discussed later in Chapter 2.3.3.

The toxicity of crude oil depends on the chemical composition and the degree of weathering. Fresh crude oils may contain monocyclic aromatics, such as benzene, toluene, ethylbenzene, and xylene (BTEX), which are highly toxic compounds. Because of their high volatility, they are not considered to be of great concern. The less volatile polycyclic aromatic hydrocarbons (PAHs) are considered to be a greater hazard as they do no evaporate as easily and have a higher solubility rate, increasing the bioavailability. This means that the compounds are in a form that makes them more readily taken up by organisms. [18].

There are different ways of assessing the impact of oil in organisms. A dose-response study examines and compares the whole organism effects in test organisms exposed to different concentrations of a substance. Dose response studies for several Arctic species exposed to oil have been performed. The results of a study regarding the Atlantic halibut larvae are presented in Figure 2.2 and Figure 2.3. Larvae were exposed to 4 different concentrations of mechanically dispersed oil from the Goliat field for 4 weeks. The dispersed oil droplet sizes ranged from 1.6 to 50 μm. The no observable effect concentration (NOEC) was determined to be 0.25 mg/L and the lowest observable effect concentration (LOEC) was determined to be 0.75 mg/L (Figure 2.2). Study showed that the exposure of halibut larvae to oil concentrations above 0.25 mg/L results in increased mortality [19].

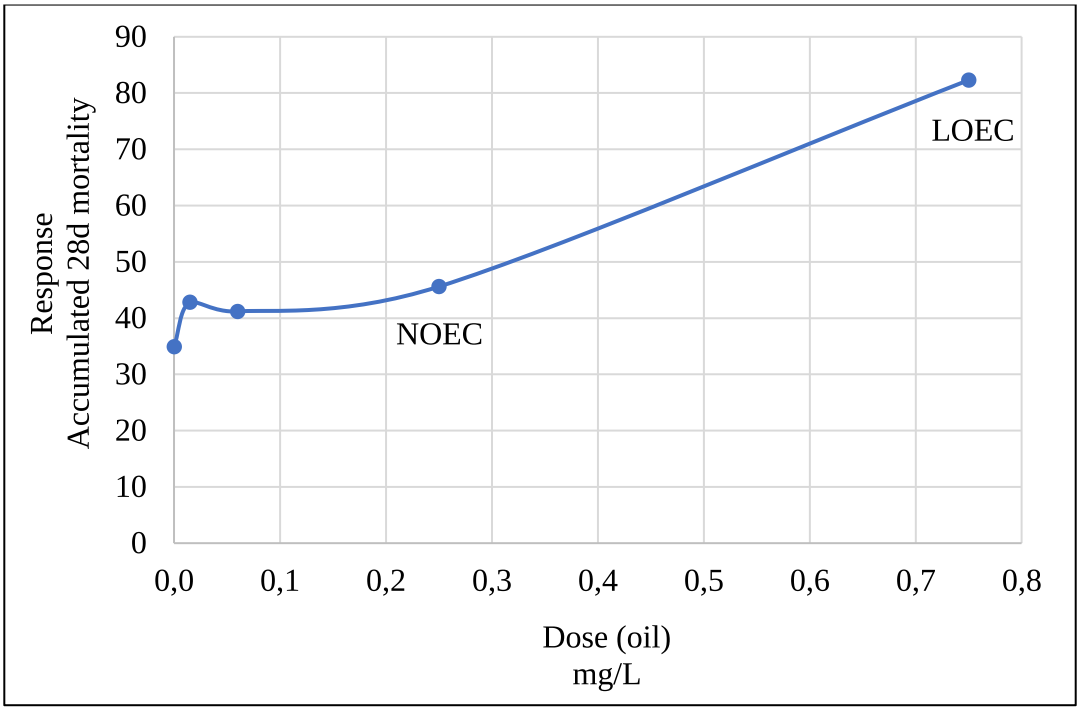


Figure 2.2 Dose-response curve created based on data from research study on Atlantic Halibut [19]. Table of data used to create the graph is presented in Appendix 1.

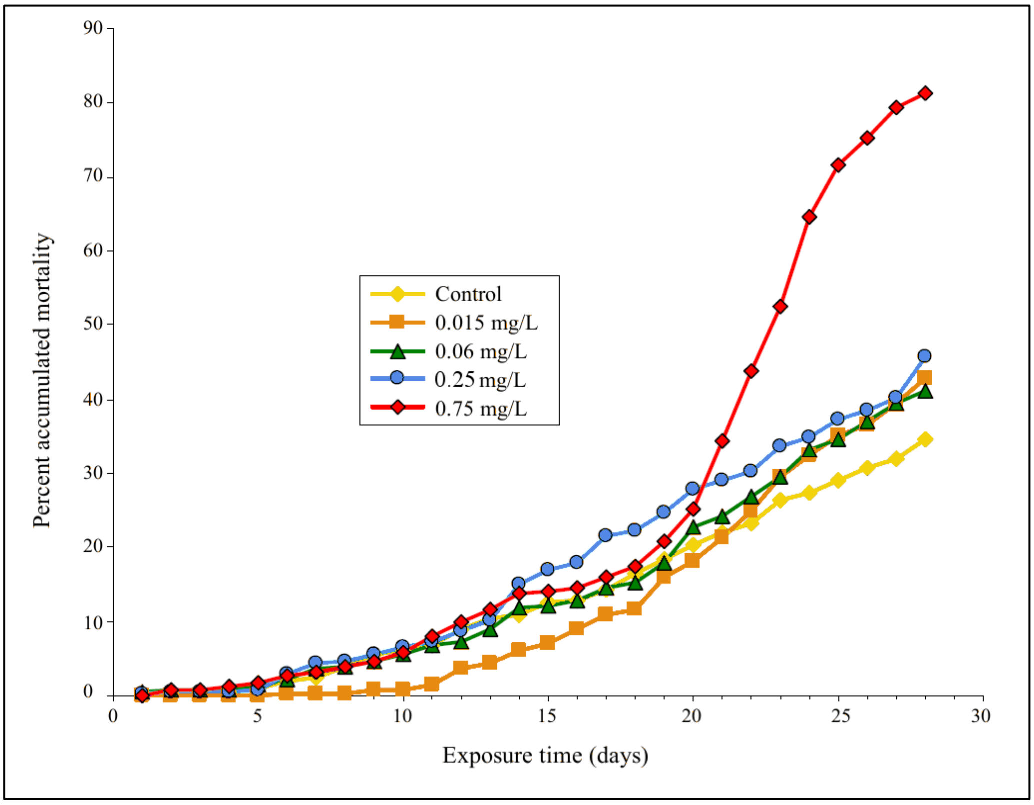


Figure 2.3 Percent accumulated mortality of Atlantic halibut exposed to Goliat Kobbe oil of different concentrations with increasing exposure time. Figure is modified from Ingvarsdottir [19].

A dose-response study cannot be performed on all species and the degree of impact is not limited to toxicity alone. For birds, the greatest risk is fouling of the feathers. To assess the impact of an oil spill on birds, Equation 1 can be used to calculate the number of killed individuals.

$$Number\ of\ killed\ birds = \sum_{i=1}^{n_i} N * P(\%) * A(\%) \tag{1}$$

The number of individuals, N, in square n_i is determined based on observations. The vulnerability, P, is based on the probability of encountering oil and the probability that the encounter will result in death. The probability that a bird will die if it comes in contact with oil is assumed to be 100 %, and the vulnerability therefore depends on how much time the species spend on the water surface. Guillemots and puffins spend the majority of their time on the water surface, hence they have a vulnerability of 99 %. Whereas kittiwakes, which spend much less time out on the water surface, have a vulnerability of 35 %. A is the percentage of the area with an oil slick thickness above a certain thickness. There are no universal limit to how thick the oil slick must be to pose a risk, but 10 μm is often used [20].

2.3 The fate of oil

A crude oil, the unrefined petroleum product, is mainly composed of hydrocarbon compounds with some sulphur, nitrogen, oxygen, mineral salts, and trace metals to a varying degree. The fate of the spilled oil depends on the chemistry of the oil, its properties and the weathering process.

2.3.1 Oil properties

The chemical composition and properties of a crude oil depends on its original substance, whether it is of plant, animal, or mineral origin, and on the geological formation where it is transformed [21]. Some of the properties that are of importance to determine the spreading of the oil and the effectiveness of oil spill response systems are further discussed.

2.3.1.1 Specific gravity

The specific gravity is a way of describing the relative density of an oil compared to pure water. Pure water has a specific gravity of 1, while sea water lies around 1.03 [21]. For most crude oils the specific gravity is lower than that for water and it will therefore float on the water surface, whilst in the opposite case, the oil will sink. The American Petroleum Institute gravity scale (API) is a scale commonly used in the petroleum industry to describe the relative density of petroleum liquids, expressed in degrees. The API gravity also says something about the composition of light and heavy compounds, hence it is an indicator of concentrations of volatile compounds and possible evaporative loss [22]. The API is calculated using Equation 2 where the specific gravity of the oil, SG, is measured at 15.5 °C.

$$°API = \frac{141.5}{SG} - 131.5 \tag{2}$$

2.3.1.2 Pour point

The pour point of a crude oil is by definition a given temperature when the oil takes longer than a specific time to pour from a standard measuring vessel [21]. In the field, the oil can remain a liquid in water temperatures down to 10 to 15 °C below the pour point due to the movement of the sea [23]. The pour point and the solidification temperature are two terms often interpreted to be the same. This is not the case, as the oil is still a fluid or semi-solid at the pour point, whereas at the solidification temperature the oil is in theory solidified. The solidification temperature is 3 to 5 °C below the pour point.

2.3.1.3 Viscosity

Viscosity is maybe the most important oil property regarding oil spill responses as it greatly affects how effective a method will be [24]. The viscosity provides information about how easily the liquid will flow. Oils of low viscosity will flow more easily than oils of high viscosity. How viscous the oil is, depends on the components of the oil and the ambient temperature. Oils containing mostly light components, such as short saturates, will have a low viscosity, whereas oils containing heavy compounds, such as asphaltenes, will have a higher viscosity [21].

2.3.2 Oil types

Different types of oils can be differentiated based on their chemical composition and properties, such as specific gravity and viscosity. In an oil spill situation, the type of oil that is spilled determines which recovery method will have the highest effectiveness. The impact on the ecosystem is dependent on the type of oil as different oils have varying residence time in the marine environment. The toxicity and bioavailability are also determined based on the oils chemical composition and properties.

2.3.2.1 Light crude oil

A light crude oil is a low viscosity oil with an API gravity above 31.3. This type of oil contains a large number of n-alkanes and aromatics. Once spilled, the oil forms a very thin slick on the water surface. As the oil weathers, the lower n-alkanes and shorter aromatics will evaporate and a large volume will readily disperse and dissolve into the water column due to the high solubility [21, 25]. Light crude oils, together with gasoline and diesel fuel, are among the most toxic petroleum products in the marine environment because of high concentrations of BTEX. Because of their high solubility in water and high dispersion rate, they are also more bioavailable than other oil types. However, due to the high volatility, the most toxic components will quickly evaporate [26].

2.3.2.2 Medium crude oil

Medium crude oils have an API gravity between 22.3 and 31.1. They are heavier than light crude oils due to a larger proportion of the heavier compounds. They have a larger concentration of PAHs and persist in the environment for a longer period compared to lighter crude oils [26]. This makes a medium crude oil more hazardous than a light crude oil, however the toxic components will be less bioavailable due to lower solubility [18].

2.3.2.3 Heavy crude oil

A heavy crude oil is a high viscosity oil with an API gravity below 22.3. This type of oil is also composed of mostly saturates and have a higher concentration of resins and asphaltenes [21]. It can form slicks up to several mm thickness with formation of tarballs and tar mats [25]. Heavy oils are of low risk to fish and organisms living in the water column as they have low solubility. Instead they impose a great risk to diving birds and mammals exploiting the water surface as it remains as a thick layer and can cover large areas. Weathering processes progress very slowly in heavy crude oils [21].

2.3.3 Oil weathering processes

Once the oil is spilled, different processes that changes the oil properties start to occur. They do not all occur simultaneously and will vary in degrees depending on the oil properties and environmental conditions. A general timeline for the most important oil weathering processes is illustrated in Figure 2.4.

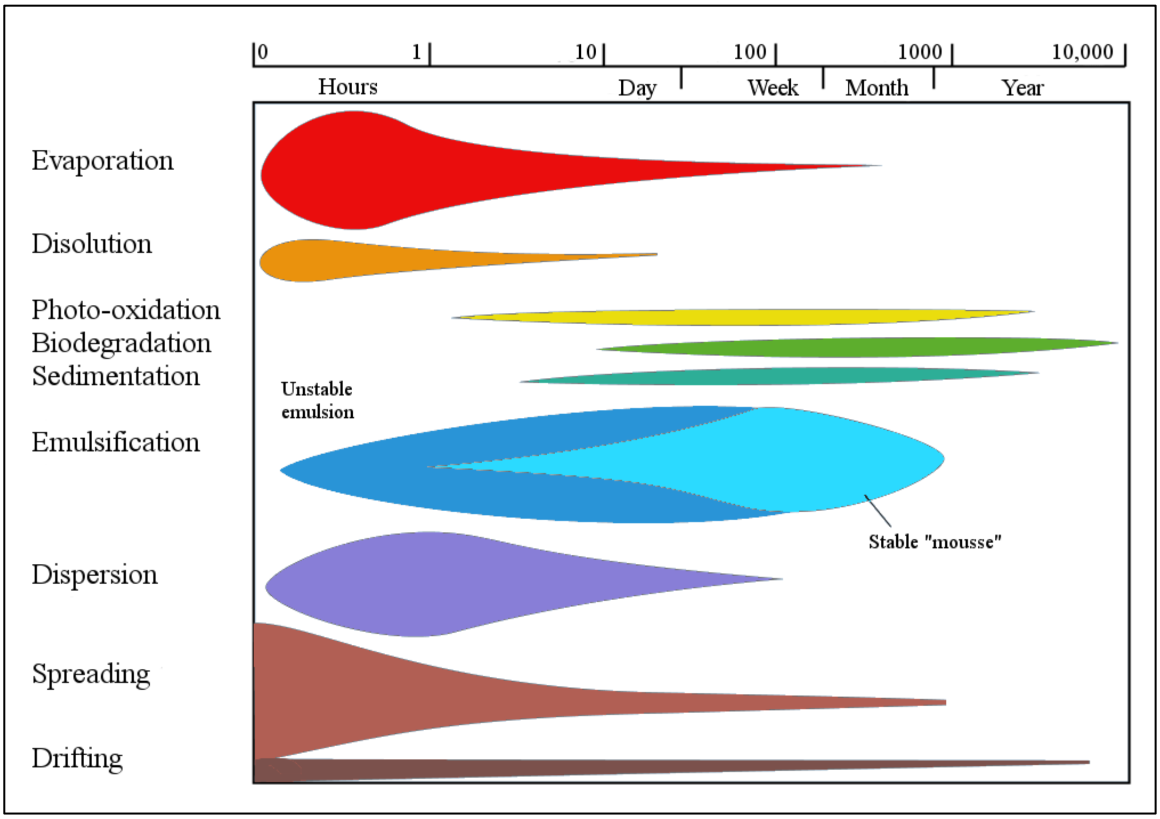


Figure 2.4 Timeline for the most important oil weathering processes (Figure modified from Fingas [25]).

2.3.3.1 Spreading

Once the oil is spilled onto the surface it will spread out. The distribution of the oil on the water surface depends on the oceanographic conditions such as wind, wave, and currents. The viscosity of the oil determines how much the oil will spread. Low viscosity oils spread fast and form thin oil sheens, while oils of higher viscosity spread slower and maintain a greater thickness. As the oil spreads, the colour of the slick will change according to the thickness of the layer. The oil does not spread homogenously and tend to break up and form as concave or convex lenses with more oil in the centre or to the sides [27].

2.3.3.2 Evaporation

Evaporation is the transport of volatile compounds from the oil slick to the atmosphere. This process starts as soon as the oil is spilled and the rate of evaporation depends on the area of the slick and weather conditions. It is an important process, as it removes the highly toxic VOC. After losing its volatile compounds, the remaining oil will have a greater density, pour point, and viscosity [23]. The evaporative loss depends on the temperature and surface area of the slick. Hence, in a colder environment and in presence of ice where the oil is contained, evaporation may be lowered [13].

2.3.3.3 Dispersion

Natural dispersion is the formation of oil droplets which are mixed into the water column. Sufficient water surface energy must be present for this process to occur. Depending on the amount of subsurface currents and turbulence in the water column, oil droplets larger than 45 to 50 μm will often resurface and form thin oil sheens. The dispersion rate depends on the viscosity of the oil, where lower viscosity means greater dispersion. The dispersion will therefore decrease as the lighter volatile compounds evaporate [23].

2.3.3.4 Emulsification

Water-in-oil emulsification is the process where small water droplets are incorporated into the oil. Oils of low viscosity form emulsions faster than less viscous oils and the stability of the water droplets increases with the concentration of asphaltenes and resins [28]. Stable emulsions can hold a volume of up to 80 % water [29].

2.3.3.5 Dissolution

Dissolution is the process where the soluble compounds of the oil are dissolved into the underlying water. Only a small amount will enter the water column and the rate of dissolution decreases as the other processes progress. However, this small amount may cause significant damage as the soluble compounds are among the most toxic compounds found in crude oil [25].

2.3.3.6 Biodegradation

Biodegradation is the breakdown of oil compounds by microorganisms. Different microorganisms can only process and digest specific compounds, and the oil droplet must be in contact with water to be bioavailable. Natural or chemical dispersion will therefore enhance the biodegradation rate [23].

2.3.3.7 Photo-oxidation

Photo-oxidation is the reaction between the oil and oxygen promoted by sunlight. The components will over time oxidise to resins and asphaltenes. Such a change in the composition of the oil can promote other weathering processes, e.g. formation of stable emulsions [23, 25].

2.3.3.8 Sinking and sedimentation

Oil may sink to the ocean floor by adhering onto particulate material, e.g. mineral particles or organic matter floating in the water column. In rare cases the oil becomes denser than water after a long period of weathering and sinks. Oil that is buried with sediments degrade slowly and can later reappear and again become bioavailable. Sinking of oil is more common after *in situ* burning since the product contains less light compounds and heavier pyrogenic products form [29].

2.3.4 Environmental effects on oil weathering

Variation in environmental conditions such as temperature, wind speed, and wave energy, will play a role in the oil weathering processes. Since different crude oils behave differently when spilled, weathering studies on several crude oils found on the NCS have been performed. These are made available in the Norwegian Clean Seas Accosiation for Operating Companies' (NOFO) online database. Gaining knowledge about the weathering processes of specific crude oils in different weather conditions will be of much help to determine the most effective response method in the event of an oil spill. In this thesis, the weathering study of Skrugard oil, from the Johan Castberg field in the Barents Sea, has been used to assess the environmental effects on oil weathering [23].

During the summer season, the Arctic has 24 hours daylight, which increases the rate of photo-oxidation, while in winter, this form of weathering will have almost no effect. During the cold winter season, evaporation and dissolution of the chemical compounds may also decrease if the temperature is low enough [30]. The winter and summer water temperatures in the Barents Sea only vary from 5 to 10 °C and the difference has little effect on the degree of weathering, as seen in Figure 2.5 and 2.6.

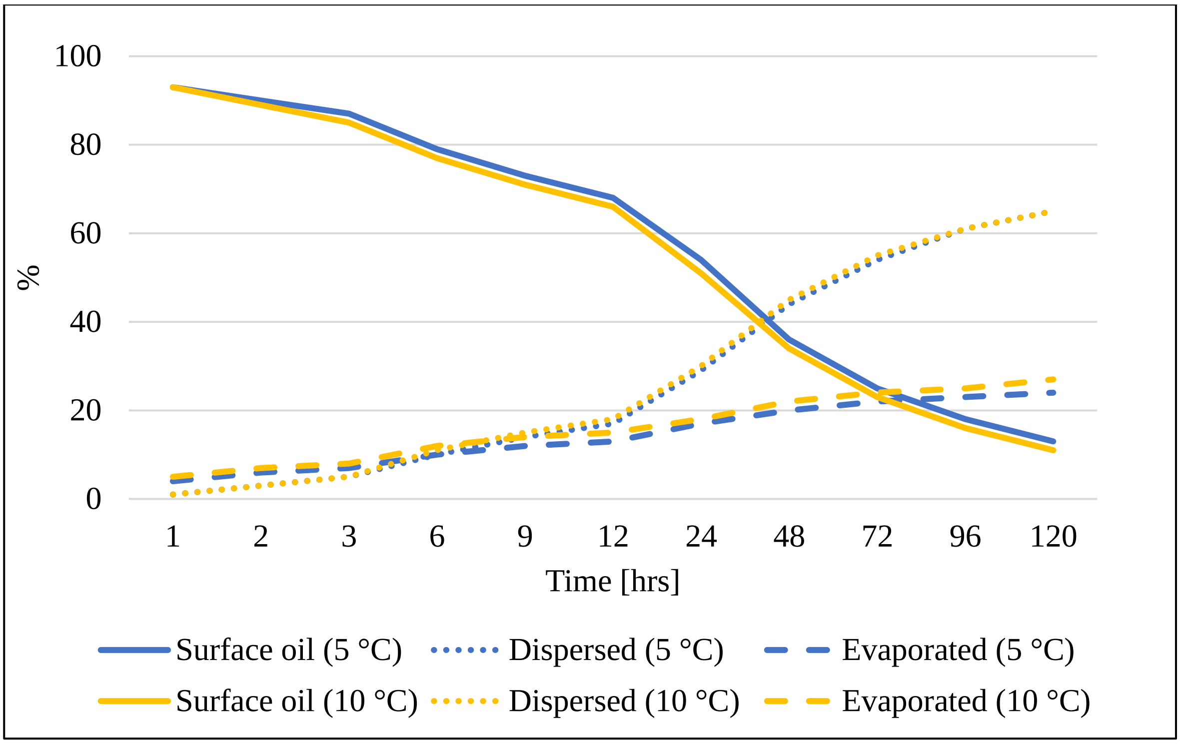


Figure 2.5 Development of weathering processes over time in winter (5 °C) and summer (10 °C) water temperatures for Skrugrad oil. The wind speed is constant at 5 m/s for all measurements. Data is collected from NOFO's database and presented in Appendix 2 [31].

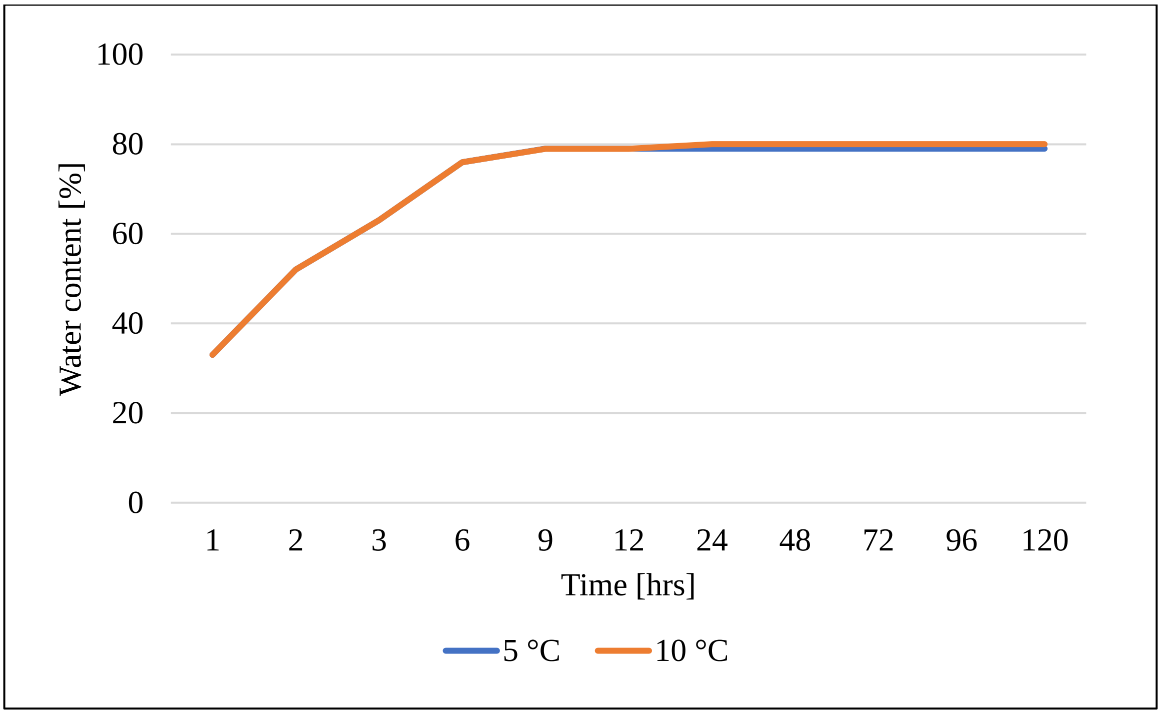


Figure 2.6 Developement of water-in-oil emulsification over time, the percentage of water uptake into the oil, in winter (5 °C) and summer (10 °C) water temperatures in Skrugard oil. The wind speed is constant at 5 m/s for all measurements. Data are collected from NOFO's database and presented in Appendix 2 [31].

Wind speed, on the other hand, has a much greater impact on the weathering processes and water-in-oil emulsification, as seen in Figure 2.7 and Figure 2.8. Therefore, when determining the oil characteristics of a spill in the Barents Sea-Lofoten management plan area, time and wind speed are the two main factors to take into consideration. The amount of wave energy and turbulence on the water surface affects the volume of oil that is broken up and naturally dispersed. In a similar way, it also affects how much water that is incorporated into the oil slick. It is not only the wave height, but also the type of wave (e.g. surging or breaking wave) that determines the degree of impact [25].

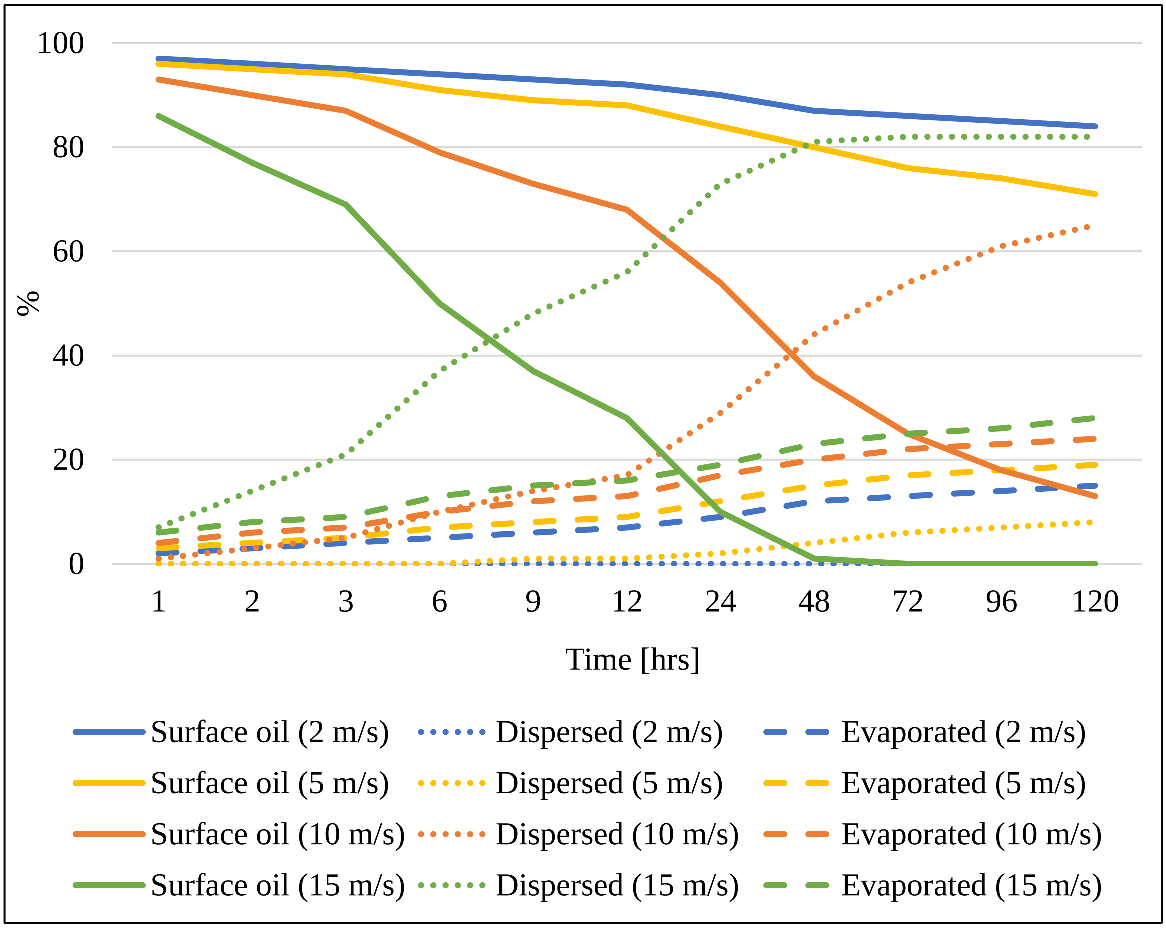


Figure 2.7 Development of weathering processes over time in wind speeds of 2, 5, 10, and 15 m/s for Skrugard oil. Water temperature is constant at 5 °C for all measurements. Data are collected from NOFO’s database and presented in Appendix 2 [31].

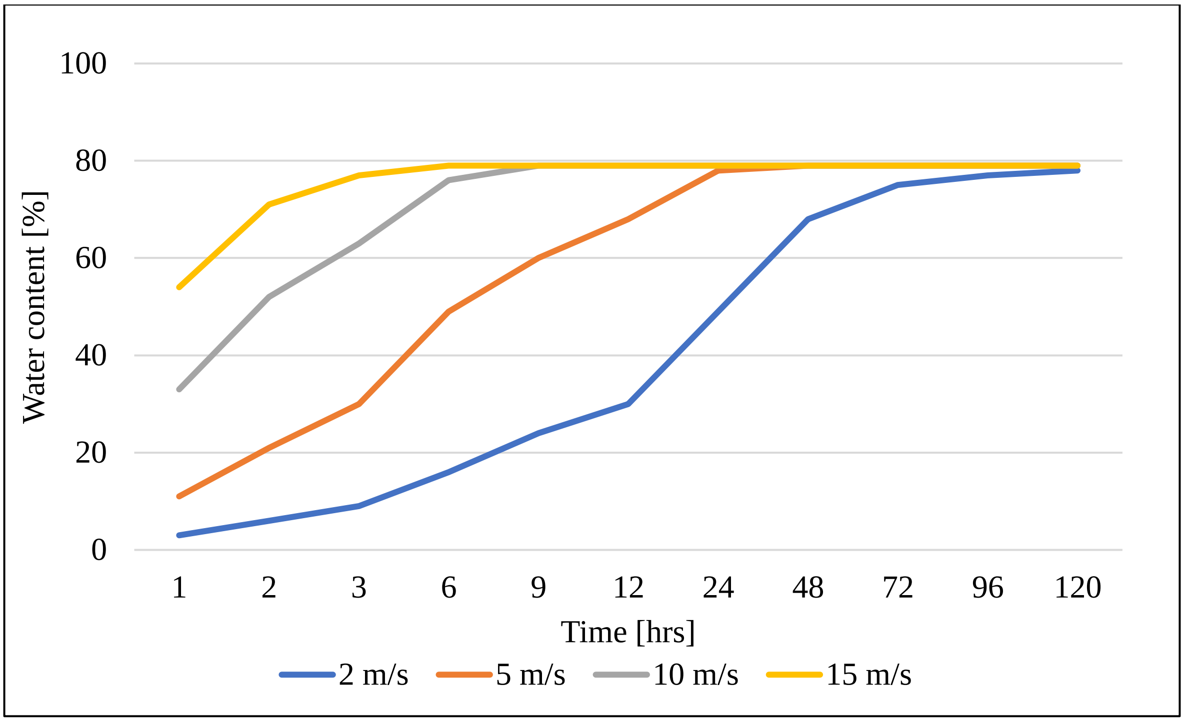


Figure 2.8 Development of water-in-oil emulsification over time, the percentage of water uptake into the oil, in wind speeds of 2, 5, 10, and 15 m/s in Skrugard oil. The water temperature is constant at 5 °C for all measurements. Data are collected from NOFO's database and presented in Appendix 2 [31].

2.4 Overview of oil spill response systems

We now know that the behavior of oil is different in cold waters compared to temperate waters and that different types of oil behave differently due to their chemical and physical characteristics. These considerations together with environmental limitations must be addressed in the response system choice. Oil spill response systems include, among others, mechanical recovery, *in situ* burning and chemical dispersion. A closer description of these three systems will be given in this section.

2.4.1 Mechanical recovery

Mechanical recovery is the containment and removal of the oil from the water surface using booms and skimmers. A boom is a floating barrier used to prevent the oil from spreading, to divert the spill away from sensitive areas, or to concentrate the spill to improve recovery. Curtain booms, as shown in Figure 2.9, are the most common type of booms [32]. They are towed from vessels or anchored to structures or land. Currents, waves and wind together with different boom parameters affect how well the booms work [32, 33]. A skimmer is a mechanical device which recovers the oil from the water surface into a temporary storage unit. Its recovery rate depends on oil properties, oil slick thickness, wave conditions, and presence of debris, such as ice [32, 34].

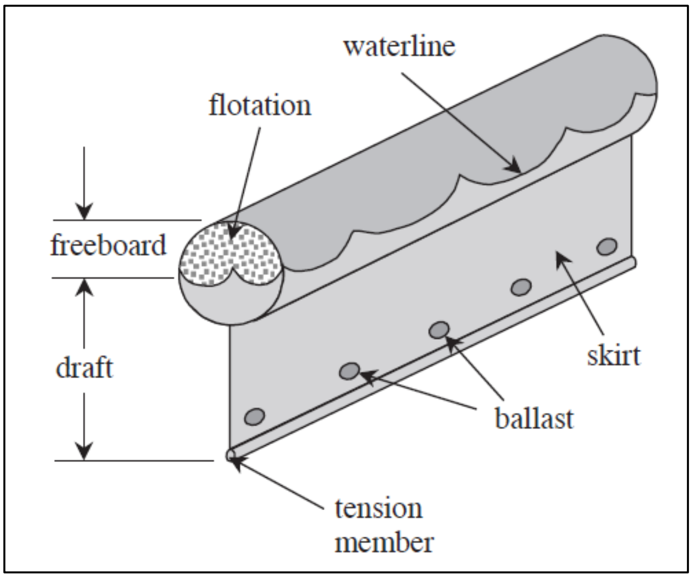


Figure 2.9 Basic construction of a curtain boom [5].

This response mechanism has so far been the preferred option in most situations as it recovers large volumes of oil from the ocean with little impact on the environment [34]. It also physically removes the oil from the environment entirely, compared to other methods where the oil is simply diluted. Mechanical recovery is the primary strategy for the Norwegian governmental preparedness and response system for acute pollution [2].

Skimmers were used during the Deepwater Horizon (DWH) oil spill, but only recovered between 75,000 to 300,000 barrels of oil, between 1.5 and 6.1 % of the total oil spilled. The low recovery rate was a result of the oil being diluted and dispersed subsea, before reaching the ocean surface. Booms were used to contain and concentrate the oil for higher effectiveness, but the process was very time-consuming. The booms were also successfully deployed at critical points to protect wildlife and sensitive areas [34].

The Arctic areas have limited infrastructure and access to equipment, and the waste must be transported over long distances. Experience has shown that mechanical equipment can be adapted to areas with presence of ice, however, its efficiency could be lowered [2]. Some adjustments must be considered, e.g. a screen could be installed in front of the intake to avoid debris from getting into the skimmer. Oleophilic skimmers (e.g. rope mops, sorbent lifting belts, drums, paddle belts and brushes) have been proven to be particularly useful in the presence of ice [22, 32]. The oil adheres to the surface of a oleophilic material, which in turn is scraped or squeezed into a storage unit [35]. The main principle of a drum skimmer is illustrated in Figure 2.10. This mechanism results in a high oil-to-water recovery ratio [32].

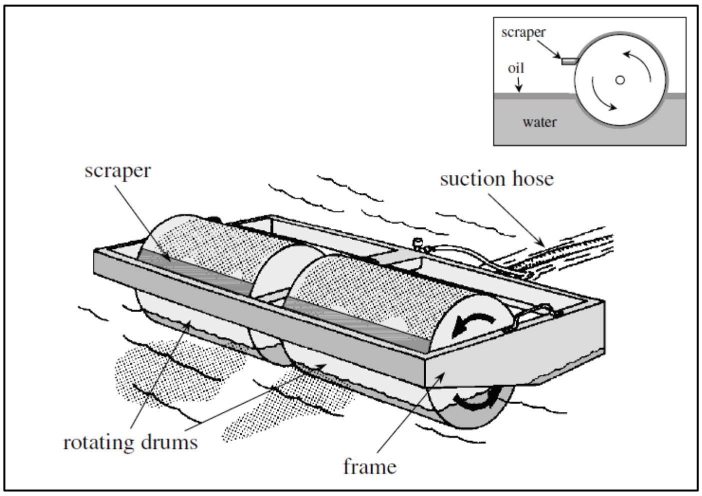


Figure 2.10 Illustration of the main principles of a drum skimmer [5].

Mechanical recovery requires much equipment and personnel, it is time-consuming and produces a large amount of waste. The recovered oil must be temporarily stored and later transported to be disposed according to regulations. The recovered oil can sometimes be reused, however, this requires reprocessing due to high water content and debris and it is a costly process which often exceeds the economic value of the product [32].

2.4.2 *In situ* burning

In situ burning was the first technique to be used as an oil spill response technique. The application is simple, requires little equipment and removes oil efficiently with minimal waste [28, 34]. The rapid removal of oil reduces the chances of the oil spill reaching sensitive areas. An oil slick on the water surface is ignited by either using an ignition device from a boat or by releasing burning, gelled fuel from a helicopter [36]. By burning the oil, the pollution is transferred to the atmosphere where it is quickly dispersed [37]. The effectiveness depends mainly on the thickness of the oil slick, followed by type of fuel and volume of water in the oil.

During the DWH oil spill, *in situ* burning was a successful response method used to remove oil from the water surface. They had 396 effective burns which removed around 300,000 barrels of spilled oil, making up 4.5 to 6.3 % of the total oil spill [38]. Even though it can be incredibly successful, this method is not used on the NCS and Norwegian operators have very little experience with it [10]. According to NOFO, *in situ* burning has not been considered a response method because the weather limitations are too narrow for the conditions experienced in the Barents Sea-Lofoten management area [39].

Many tests have been carried out to see if *in situ* burning have the same effectiveness in the Arctic environment as in the temperate one [40]. The burn rate of different crude oils in water varies between 0.5 and 4 mm/min. According to Fingas [38], the burn rate is reduced to 1-2 mm/min in the presence of ice, half of the rate expected in open water. However, in 2006 Dickins et al. carried out an experiment on Svalbard, where they observed the effectiveness of *in situ* burning on ice [41]. Contrary to Fingas' results, the found the average burn rate to be estimated to 3.1 mm/min with an effectiveness of 96 %. The conclusion after the experiment was that *in situ* burning can be an effective response method that greatly reduce the environmental impact of oil spills in areas of ice with limited logistical possibilities [41].

Figure 2.11 *In situ* burning of weathered free-floating oil in high ice cover during a field experiment in the Barents Sea [8].

2.4.3 Chemical dispersants

Chemical dispersants are a mixture of surfactants and solvents that reduce the natural forces within the oil [34]. Surfactants are molecules with a hydrophilic and a lipophilic component. This characteristic causes the oil to disperse in the water column as smaller droplets. Figure 2.12 illustrates the processes included. Smaller droplets are assumed to enhance the oil biodegradation rate in the water column, but also result in an increased oil bioavailability to marine organisms [27, 34]. Increased dissolution of oil in water decreases the evaporation of volatiles, which in turn enhances the safety for clean-up personnel [34].

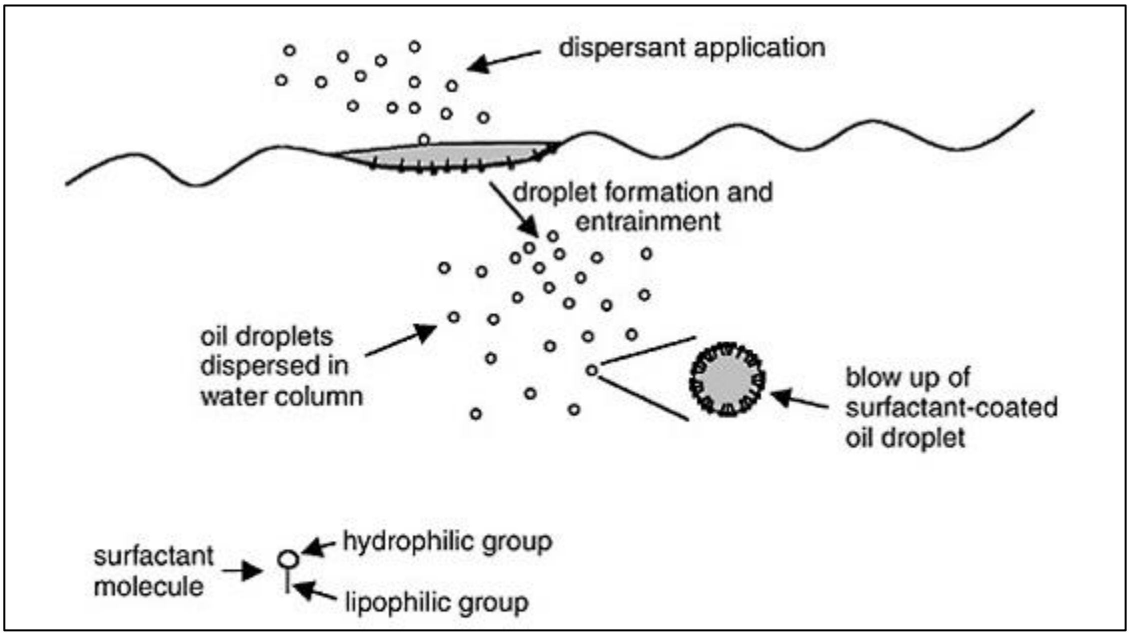


Figure 2.12 The chemical dispersion process – the process where surfactants reduce the interfacial tension between the two liquid phases. Droplets form and are dispersed into the water column by turbulent energy [42].

Figure 2.13 shows the concentration distribution of different types of oils at 1, 5, and 9 m depths after the slicks have been treated with the dispersant Corexit 9500. The threshold level is the lowest detected value of LC_{10} for the tested individuals. LC_{10} is the lethal concentration where 10 % of the sample population are killed. The data shows that 50 minutes after the application of a dispersant the oil concentrations are reduced to below acute toxic levels [43].

Dispersants are primarily used to minimize oil spill impacts along the shorelines and in sensitive areas, as well as to promote biodegradation of the oil. The effectiveness of dispersants depends on type of oil, followed by wave energy and temperature [27, 34]. It can be applied in two ways; by spraying directly onto a surface oil slick from a ship or airplane, or injected subsurface directly into the wellhead stream [34]. The latter method was first used in full scale during the DWH oil spill in 2010 and was proven to be very successful. Around 7000 m^3 of dispersant was used during this accident. It is assumed that about 500,000 bbl of oil was dispersed, making up 10.2 % of the total oil spill. The Arctic environment is different from the Gulf of Mexico and the technology has not yet been modified to suit ice covered areas. However, simulations and experiments show good indications that it will also be a successful response method in the Arctic [2, 40]

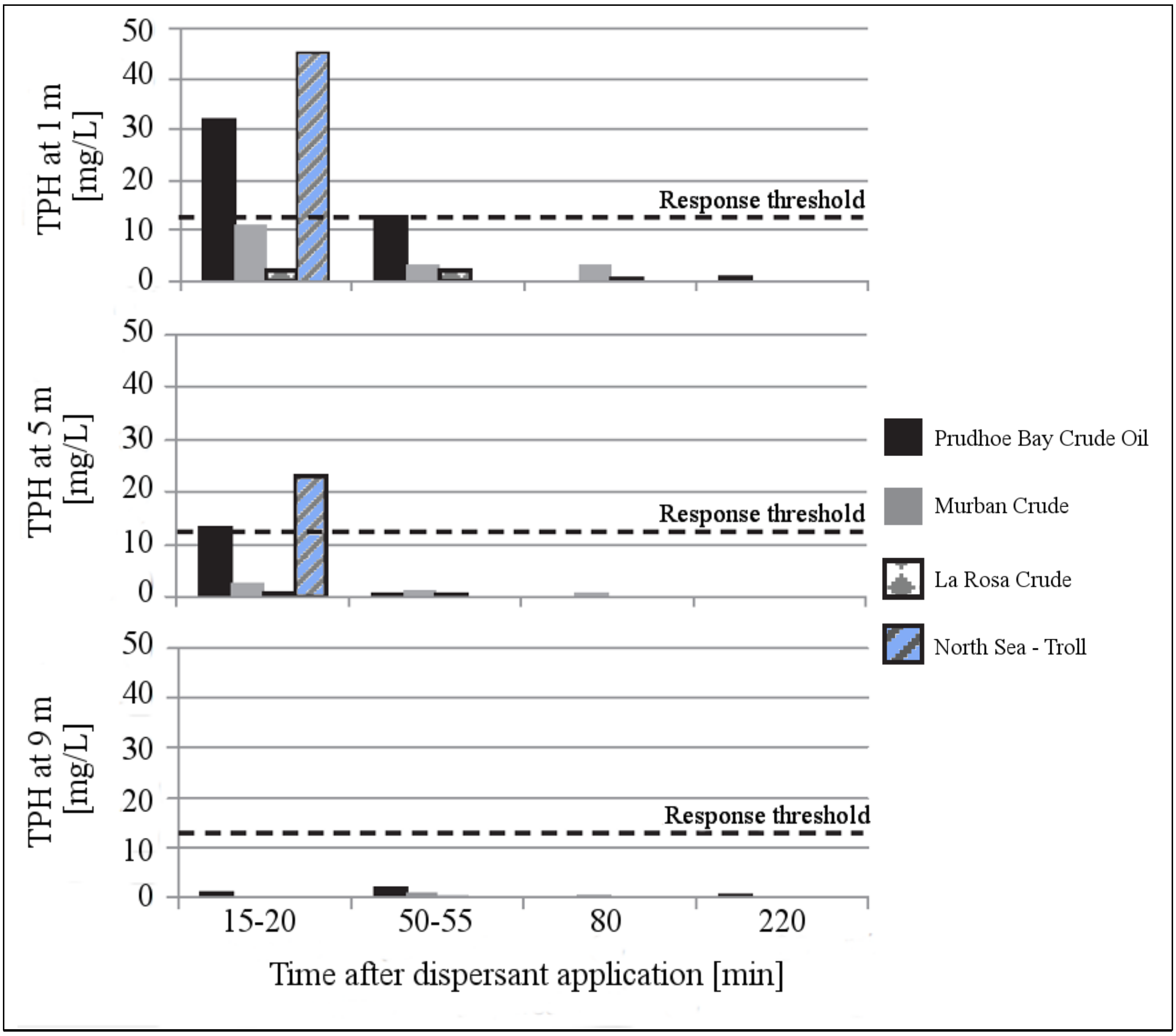


Figure 2.13 Dilution of total petroleum hydrocarbon (TPH) concentrations over time in water depths of 1, 5 and 9 m after applying Corexit 9500 dispersant chemical. The response threshold is the lowest value of LC_{10} for the tested Arctic species [43].

It is important to make sure that the spilled oil is dispersible. If the dispersant is sprayed onto the slick without any effect, other response methods must be implemented instead. The issue is that the dispersant chemicals makes the oil less adhesive and harder to recover with skimmers and sorbents [27]. Sorbents are materials developed to absorb or adsorb oil. They are most often used as a final finish to recover the residue of other response methods or on very small spills [32].

Figure 2.14 Airplane releasing dispersant onto an oil slick on the Gulf of Mexico during the DWH response [12].

2.5 Factors to assess effectiveness

Spreading and degradation of oil in the Arctic will progress differently from temperate areas due to lower temperatures, harsher weather, less sunlight, and the presence of sea ice. Exploration companies expand their search for hydrocarbons to more remote areas with less infrastructure and further away from emergency equipment. The environmental conditions and longer response time are some of the factors that must be considered in a model to determine the effectiveness of response systems in the Arctic.

2.5.1 Environmental limitations

The Arctic is characterised by long freezing winters and short cool summers. However, the Barents Sea is not like the other Arctic oceans. The southwest part of the Barents Sea experiences sea surface temperatures as high as 4 °C, whereas in the north and east, the temperature can decline to as low as -2 °C. The main reason for this large difference is the influx of warmer water from the Gulf Stream into the southeast Barents Sea. In winter, the air temperature can drop as low as -20 °C close to the Norwegian mainland coast and -40 °C near Svalbard. Big differences between the sea and air temperatures create harsh, rapid changing climate conditions in these areas which are difficult to forecast.

During the winter season, cold air from the ice-covered areas blows towards the warmer ocean. The air will rise and create a polar low which can make a breeze increase to a storm within minutes, and waves have been measured to rise 5 m in less than 1 hour. The warm water from the Gulf Stream also produces much precipitation and clouds, which can reduce the visibility. During the summer season the temperature differences are the opposite, and warmer air will blow over colder sea and cool down, resulting in a thick fog.

When planning an oil spill response in the Barents Sea, the first decision to be made is whether or not a response actually is possible. Challenging conditions with freezing temperatures, sea ice, high waves and wind, and total darkness for up to three months of the year, can delay the response or even make it impossible for certain periods. These periods, when the maximum operation limit for an oil spill response system is exceeded by the environmental conditions, are referred to as oil spill response gaps [44]. According to a study done by Nuka Research and Planning Group LLC, sea ice is the most important environmental factor preventing oil spill response in the Arctic [45]. The ice is a dynamic system and every year it goes through periods of freeze-up, solid ice, break-up and open water. Each season presents different challenges, which again will require different response approaches. A summary of the main limiting parameters for different response systems are presented in Table 2.1.

2.5.1.1 Wind

Mechanical recovery can operate in winds up to 15 m/s, but the effectiveness of the system is lowered above 10 m/s. Above 10 m/s, both containment and recovery are inefficient. *In situ* burning is also unfavourable above 10 m/s as it becomes difficult to ignite and maintain a burn in higher wind speed. Dispersant may be used in wind speeds up to 15 m/s, but the effectiveness is halved when reaching 10 m/s as problems targeting the oil slick may arise [45]. Field tests indicate that optimum wind speed for dispersion is between 4 and 12 m/s [46].

2.5.1.2 Wave

Both mechanical recovery and *in situ* burning are unfavourable when the wave height reaches 2 m, and even before this if the waves are breaking. High waves make it difficult to contain the oil for recovery or burning. Dispersants may be the preferred option in rough sea and can be applied efficiently in wave heights up to 3 m. The method requires mixing energy for the oil to break up into smaller droplets, and in calm weather, vessel propellers or bow thrusters can be used to add the required turbulence [45]. In cases with breaking waves over 1 m, natural dispersion might be more effective than any response [47].

2.5.1.3 Temperature

Low temperatures make the oil more viscous, and if the ambient temperature is near the solidification temperature, the oil will potentially solidify. Dispersants are only effective on oil in fluid form with viscosity less than 10,000 cSt. If the oil solidifies, collection equipment such as nets and shovels are required [22]. Yet, temperature is mainly a limiting factor associated with safety for personnel rather than the effectiveness of a recovery system. Personnel's physical, mental and emotional abilities are proven to decline in extreme cold conditions. This reduction results in an increase in the risk for work accidents. Most equipment has a temperature-operating limit which must be taken into consideration, but most times other factors stop the operation before this limit is reached. Icing is one of the first issues one might encounter in low temperatures and it can affect the vessel stability [45].

2.5.1.4 Ice cover

The sea ice in the Barents Sea varies greatly, reaching its maximum extent in April and its minimum in September [2]. Unstable and moving ice can damage the vessel and the equipment. Ice and slush reduce the access and flow of the oil to the skimmer and may cause clogging. Still, it has been proven that mechanical equipment, adapted to handle debris, can be utilized in areas of ice up to 30 % coverage. Ice has been known to dampen waves and therefore reduce the mixing energy and effectiveness of dispersants [45]. However, a recent study showed the opposite, that the interaction between broken ice enhances dispersion [47]. As mentioned earlier, vessels capable of operating in ice-covered areas can be used to generate wave energy. Dispersants have therefore been proven to be effective in ice concentrations as high as 90 %.

In ice concentrations higher than 90 %, either *in situ* burning or mechanical recovery can be used, depending on the stability and safety of the ice. The presence of ice can make it harder to ignite the oil, but may work as natural containment and help maintain the necessary oil slick thickness [45]. Modelling of oil spills using the Oil Spill Contingency and Response (OSCAR) model showed that in 40 % static ice concentration there was a 90 % spreading reduction [12]. The OSCAR model is a simulation tool created by SINTEF. By accounting for weathering, physical, biological, and chemical processes that may affect the oil, the model predicts its fate after an oil spill. The model can with some degree of uncertainty forecast a potential spill and is used in planning the response [48].

2.5.1.5 Visibility

Fog and snowstorms will at times reduce the visibility, thus limit the quality of the response. In extreme examples of this, with no available sunlight during the winter months, a response will be nearly impossible. The Barents Sea is located at a latitude so far north that the sun barely rises above the horizon during the winter season. This period of total darkness is called the polar nights. They are rewarded by the midnight sun in the summer, with almost 24 hours daylight [49]. Vessels and airplanes depend on a certain level of visibility to operate safely. Vessels require between 0.125 and 0.5 nautical miles, depending on daylight and darkness, while airplanes are limited to daylight and visibility of at least 0.5 nautical miles in uncontrolled airspace. For all response systems one must be able to track the oil slick and deploy equipment in a safe manner [45]. New technology has improved the operation time and infrared radiation (IR) cameras have been successfully used to operate in total darkness.

Table 2.1 Summary of environmental response limits. Values are valid for response in open water. Data are collected from various sources and converted to SI units [22, 45, 47, 50].

	Wind [m/s]	Wave height [m]	Temperature (wind chill) [°C]	Ice concentration [%]	Visibility [nautical miles]
Mechanical recovery	< 15	< 3	-37	< 30	> 0.125 (daylight) > 0.5 (darkness)
In situ burning	< 10	< 2	-37	< 30 or > 90	> 0.5 (daylight aerial) > 0.125 (daylight vessel) > 0.5 (darkness vessel)
Dispersants	< 15	< 3	-37	< 50 aerial < 90 vessel	> 0.5 (daylight aerial) > 0.125 (aylight vessel) > 0.5 (darkness vessel)

2.5.1.6 Oil spill response gaps in the Barents Sea-Lofoten management plan area

Because of the environmental conditions in the Barents Sea-Lofoten management plan area, it will sometimes be impossible to implement a response system. The periods of response gaps are highly dependent on the seasonal variations. DNV GL has calculated the average response applicability based on operational limits set for the response systems and the expected environmental conditions in the Barents Sea (Table 2.2). It should be emphasised that these values do not represent the effectiveness and how much oil that may be recovered. It only states the potential for implementing the given response systems with respect to the expected weather in the Barents Sea [50].

Table 2.2 Average applicability for each response system in each season due to environmental conditions [50].

	Mechanical recovery	In situ burning	Vessel-based dispersion
Spring (March – May)	45 %	21 %	48 %
Summer (June – Aug)	76 %	44 %	77 %
Autumn (Sep – Nov)	52 %	16 %	55 %
Winter (Dec – Feb)	38 %	9 %	43 %

2.5.2 Response time

In the White Paper Meld. St. 20 (2014-2015) regarding the management plan for the Barents Sea, the Norwegian Government writes *"finding efficient logistics solutions will be a major challenge for all types of operations in Arctic waters"* [2]. It is a major challenge because large parts of the Barents Sea have little to no infrastructure and limited communication. The distances between the sites are long and the available response equipment, vessels and storage capacity are limited and often far away.

A rapid response is crucial when trying to maximise the recovery and minimise the impact of an oil spill. The Norwegian Coastal Administration (NCA) is responsible for the response on behalf of the Government. They have their main northern depots in Bodø, Lødingen, Tromsø, Hammerfest, Vadsø and Longyearbyen. However, the governmental emergency response system is mainly designed to respond to shipping accidents and not large oil spills. The operators on the NCS are therefore expected to provide a response plan themselves, based on the needs of their ongoing operations. They are assisted by NOFO who, on behalf of the operators, plan and implement the emergency responses [10]. NOFO’s bases and depots of relevance to the Barents Sea are located in Hammerfest, Tromsø, Hasvik, Havøysund , and Longyearbyen [51].

Based on the guidelines from NOROG, the first response barrier must be in place within the minimum calculated time it takes for the first oil particle to drift to shore or reach a sensitive area. The response time is the total time from when the response team is alarmed and until they start a response on the spill location. How long the response time is, depends on required time to mobilise, distance and speed of the vessel or airplane, and time needed to prepare and deploy the equipment [52].

Weathering and evaporation of the spilled oil is slowed down in lower temperatures, which means that the window of opportunity is prolonged, and the chances of an effective response is increased. An experiment executed by Brandvik et al. near Hopen Island in the Barents Sea, showed that if the oil is trapped in or under ice, the weathering is even slower [40]. Normally, crude oils are burnable for 2 to 5 days, but if trapped in or under ice, the oil may be burnable for months [22]. Oil viscosity increases in cold water and can make dispersants less effective. The viscosity also increases as the oil weathers, and dispersants should therefore be applied as soon as possible [47].

2.5.3 Cost

The average cost of an oil spill response ranges from 20 to 200 USD/L worldwide, but are difficult to determine more precisely due to the influence of many factors [53]. According to Prendergast and Gschwend, the costs related to a spill can be divided into three categories: the clean-up costs, the environmental costs, and the socio-economic costs [54]. The clean-up costs are the expenses related to the oil recovery itself and associated research. The environmental costs accounts for the expenses related to the ecosystem impact and wildlife rescue. The socio-economic costs cover the expenses related to compensation for economic losses within e.g. fishing industry or tourism.

Different estimation models have been developed and what they all have in common, are the main factors identified as the most influencing relative to the cost. They are the type of oil, the extent of shoreline oiling, spill volume, location (both geographically and national jurisdiction), and response method [54-57]. Weather and season are also mentioned to be important factors, but have not yet been implemented into any models. Montewka identifies oil type as the most influential factor as it accounts for how the oil spreads, the time it takes for the oil to reach shore, and the efficiency of the response system [57]. The cost increases with the weight and viscosity of the oil. Heavier oil is more difficult to recover and causes greater environmental impacts due to longer persistence in the nature and greater environmental impact. According to Etkin, in 1999, Norway was the fifth most expensive country for performing marine oil spill clean-ups with an average per-unit cost of USD 23,111.08 [56].

Based on the cost model used by Prendergast and Gschwend [54], the most expensive recovery system is mechanical recovery, followed by dispersants and *in situ* burning. The least expensive option, *in situ* burning, is estimated to be 5 times cheaper than mechanical recovery. If the oil reaches the coast line, the clean-up costs are expected to increase by a factor of 2.5 to 4 compared to offshore [58].

2.5.4 Effect on ecosystem

When making a decision on which response system to implement, it is important to consider the system effect on the ecosystem. The Net Environmental Benefit Analysis (NEBA) is a decision-making tool that evaluates the possible environmental risks and benefits of different response systems [36]. The analysis has so far had focus on the short-term impacts but is now being developed to also include the long-term effects and the resilience of ecosystems. Because of a longer response time to the more remote areas, it is highly important to also take into consideration that Arctic species will experience longer exposure to the oil. Researchers are working towards developing a process for better ecological consequence assessment for different response systems [59]. The environmental impact may vary for different ecosystems, depending on key species, size of populations etc.

The Spill Impact Mitigation Assessment (SIMA) is a refinement of NEBA, after a debate shed light on the fact that in practice the selection of a response system is done based on more than just environmental considerations. SIMA is developed to include both ecological, socio-economic and cultural aspects [60].

2.5.4.1 Mechanical recovery

Mechanical recovery inflicts little to no harm on the environment as it does not apply any chemicals or any major physical stress. It is also the only response method that actually removes the spilled oil from the environment. The method is very time-consuming and requires much equipment which creates noise and air pollution. The longer the oil remains on the surface, the greater is the risk of oil being ingested by organisms, contaminate the gills of fish, or foul the feathers of birds and the fur of mammals. In coastal areas, near the ice edge or sensitive areas, one must therefore consider if there is enough time to mechanically recover the oil before too much damage is inflicted.

2.5.4.2 *In situ* burning

The environmental concerns related to *in situ* burning are the air emissions during a burn and the residue left behind afterwards. When the oil burns, 85 to 95 % becomes carbon dioxide and water, 5 to 15 % is transformed into particles such as soot due to ineffective burning, and the last 1 to 3 % are other combustion by-products such as nitrogen dioxide, sulphur dioxide, carbon monoxide, and PAHs. So far, analyses show that the concentrations of toxic compounds released to the atmosphere are below the limits to cause any environmental risk [34, 38].

The residue is a semi-solid layer of tar containing mostly heavy oil components. Alkanes and cycloalkanes have been depleted in the burn, and there is a reduction in VOC, both from evaporation and burning. The total concentration of PAHs also decreases, but there is a higher proportion of larger PAHs. The higher-molecular weight PAHs have a higher carcinogenic effect, but are less soluble in water [18]. There has also been noticed an enrichment in metal concentrations, but they are believed to have low bioavailability when bound in the residue matrix [38, 61]. Most of the residue can be cleaned up after a burn using sorbents or skimmers. If it is not recovered, the residue can persist in the environment for a very long time as it is slowly biodegraded [18]. Over time, the unrecovered residue may strand on the shorelines or sink to the ocean floor.

After burning, heavy crude oil will sometimes have a greater density than water and sink as it cools [18]. Benthos are therefore considered to be one of the groups exposed to the highest risk after *in situ* burning, as they may become smothered if the residue sinks and settles on the ocean floor [61]. Overall, in comparison to the risks related to exposure to untreated crude oil, *in situ* burning decreases the environmental risk.

2.5.4.3 Chemical dispersant

By applying a dispersant, a large volume of oil can be removed from the water surface, thereby reducing the risk for organisms exploiting the water surface and coastal ecosystems. Instead, the risk increases for the organisms further down in the water column as oil droplets form and disperse. Effects on the organisms can come from both exposure to the dispersed oil and the dispersion chemical itself.

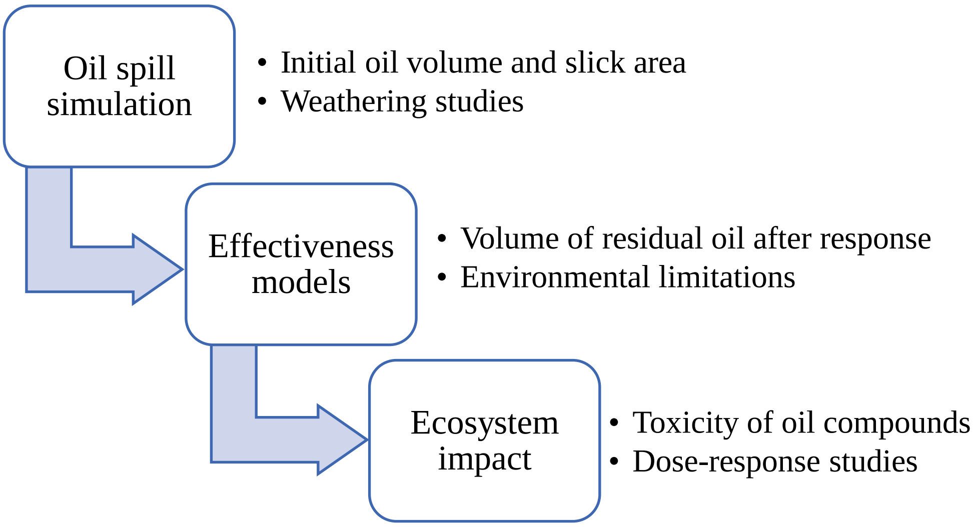
In open oceans the dispersed oil only exists in the water column for 2 to 4 hours before it is further diluted. Oil concentrations just beneath a dispersed slick have been measured to be less than 50 mg/L, and less than 1 mg/L at 10 m depth. Compared to an undispersed slick, with a concentration up to 250 mg/L beneath the slick, the application of dispersants reduces the concentration with as much as 80 %. Acute toxicity data shows that exposure to oil concentrations lower than 10 mg/L for 2 to 4 hours inflicts no adverse ecological effects on the exposed organisms [17]. The effect may vary for different species and for individuals on different stages in the life-cycle, but the overall data indicates that there is no greater risk related to dispersed oil than undispersed oil [17]. In fact, a study done by McFarlin et al. showed a significant decrease in toxicity of chemically dispersed oil compared to physically dispersed oil. The LC_{50}, i.e. the lethal concentration when 50 % of the sample population dies, for Arctic cod was measured to be 55 mg/L for chemically dispersed oil and 1.6 mg/L for physically dispersed oil.

The effects of chemical dispersants on the environment have been a highly debated topic and research has resulted in conflicting outcomes. According to the Centers for Disease Control and Prevention report, the dispersants, Corexit 9527 and 9500, which were used during the DWH oil spill, were not considered to cause any harm and contained only biodegradable and low toxicity compounds [62]. On the other hand, research done by Hamdan and Fulmer showed that exposure to the same dispersants caused inhibition in hydrocarbon-degrading bacteria, lowering the capacity of the organisms to naturally bioremediate the oil [63]. It has been recognized that some dispersant compounds in fact do have toxic effects on marine life, especially to those in an early life stage. Couillard et al. found that the use of dispersants caused an increase in total PAH, which led to a higher mortality rate in exposed mummichog larvae and a reduction in body length [64].

3. Methodology

Until this point, relevant theory for the objectives has been presented. This section will provide an overview of how the necessary theory and data was collected and further used in the thesis.

To assess the effectiveness of an oil spill response method, knowledge about a potential spill had to be obtained. Much of this knowledge could be gathered from oil spill simulations and oil weathering studies. To determine the volume of oil remaining in the environment after a response, effectiveness models were developed. Using the literature, the main factors influencing the effectiveness were identified. Based on these factors, quantitative models were attempted to be made for each individual response system. The effects of the responses were then studied, both considering the impact due to the response itself and to the decrease in oil volume. Assessment of toxicity of different oil compounds and dose-response studies were used to determine the degree of change in toxicity towards Arctic organisms with and without implementing a response. The stages to assess the effectiveness with regards to environmental risk are presented in Figure 3.1.



Oil spill simulation

- Initial oil volume and slick area
- Weathering studies

Effectiveness models

- Volume of residual oil after response
- Environmental limitations

Ecosystem impact

- Toxicity of oil compounds
- Dose-response studies

Figure 3.1 An overview of the steps to evaluate the effectiveness of the response systems.

4. Model derivation and discussion

The factors impacting the effectiveness of the response systems have now been determined through the literature study. In this chapter, they will be used to derive quantitative models to calculate the potential reduction in an oil slick. Further, the models will be used in a case study.

4.1 Derivation of effectiveness models

In order to conclude on which response system to implement, it is important to know how well the systems work under the given conditions and which factors that are the most critical and of highest influence. In a simplified way, the effectiveness of any response system can be regarded as the volume of oil removed from the surface divided by the total volume of oil spilled using Equation 3. The volume removed will be the difference between the initial, V_i, and residual, V_r, oil slick volume. As these values are often hard to retrieve in the field, other models have been developed. The models developed in this thesis are based on the theory from the literature study, by comparing existing models and adapting them to the needs required in Arctic areas [54, 65, 66].

$$Effectiveness = \frac{V_i - V_r}{V_i} \tag{3}$$

4.1.1 Mechanical recovery

The procedure for mechanical recovery is to contain the oil with booms and recover the contained oil with skimmers. The two parts can either be done simultaneously or consecutively, depending on the system. Figure 4.1 shows a system where a boom is towed in a U-formation to collect and contain the oil slick, before a skimmer is placed in the pool to recover the oil, whereas Figure 4.2 and Figure 4.3 show systems where containment and skimming are carried out simultaneously. This thesis focuses on the first strategy, which will be further discussed.

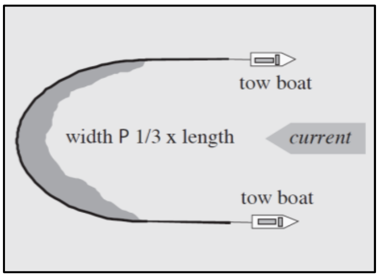


Figure 4.1 U-booming [22].

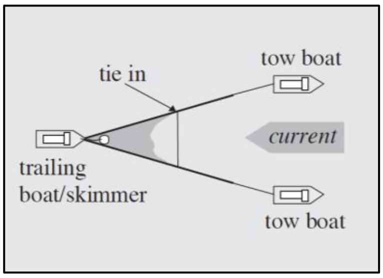


Figure 4.2 V-booming [22].

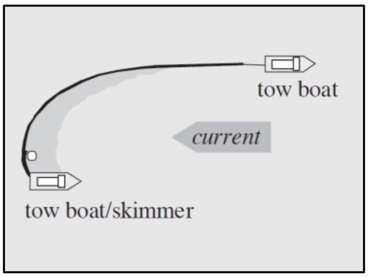


Figure 4.3 J-booming [22].

The volume of residual oil, V_r (m^3), of different response systems can be used to compare the effectiveness of each method. For mechanical recovery, the residual oil is the difference between the initially spilled oil volume, V_i (m^3), and the oil recovered, OR (m^3). The influence diagram in Figure 4.4 illustrates the factors that influence the effectiveness of the system and their dependencies. Based on these factors, another model for determining the effectiveness of mechanical recovery can be established:

$$V_r = V_i - OR \tag{4}$$

The initial oil volume, V_i, can be determined in tests, but is more difficult to assess in a real oil spill situation. Today's methods to determine the oil volume in the field are often based on the pumping rate from the well or by visual analysis of the slick using The Bonn Agreement Oil Appearance Code (BAOAC) to describe the relationship between the oil appearance and slick thickness [67]. However, because of difficulties with measuring the slick thickness, these results are only estimates and do not provide sufficient data to a valid mass balance [28]. The BAOAC and methods to determine the thickness are further discussed in Chapter 4.1.4. The initial oil volume is a function of the area of the spill, A_{spill} (m^3), and the average slick thickness, $\bar{h}$ (mm). The constant is a conversion factor for the thickness from mm to m.

$$V_i = A_{spill} * \frac{\bar{h}}{1000} \tag{5}$$

OR depends mainly on two factors: the encounter rate, ER (m^3/min), and the recovery rate, RR (m^3/min). The encounter rate describes how much oil/emulsion that is contained and available for recovery, while the recovery rate describes how much oil the skimmer manages to recover from the encountered oil/emulsion. How much oil that is recovered in total from the spill also depends on the operation time, $t_{operation}$ (min). NOROG assumes that the skimming operation is in action 50 % of the operating time, limited by environmental conditions, time spent on collecting the oil and other required activities [52].

$$OR = ER * RR * t_{operation} * 0.5 \tag{6}$$

The ER is dependent on the swath, S (m), the towing speed, v (m/s), of the recovery system, and the thickness of the oil slick. The constant in Equation 7 is a conversion factor for velocity, from seconds to minutes, and for thickness, from mm to m. The swath is the width of the skimming system opening, and a swath width of 1/3 of the boom length is normally used [54]. In the case of a boom-skimmer system, the boom is assumed to perfectly funnel the oil slick towards the skimmer so that the effective swath of the skimmer is equal to the boom opening. The towing speed of the recovery system is the velocity at which the skimmer and boom are towed, relative to the water surface. The maximum towing speed is generally set to 0.5 m/s for traditional booms, as this is the speed when entrainment failure occurs and oil slips under or splashes over the boom [22].

$$ER = S * v * h * 0.06 \tag{7}$$

The RR depends on the type of skimmer, the volume of oil recovered, V_{oil} (m^3), and the throughput efficiency, TE (%). TE is the percentage of oil/emulsion that the skimmer manages to recover from the encountered oil. It varies between different skimmers and is affected by the type of oil and degree of oil weathering. TE can be retrieved from test results of the specific skimmer unit. In the absence of such data, a default value of 75 % can be used [66].

$$RR = TE * V_{oil} \tag{8}$$

The TE includes both the oil and the emulsified water recovered, but not the free water. To calculate the V_{oil}, the percentage of emulsion, PE (%), must be determined and subtracted. From oil weathering studies, the percentage of emulsification for a specific crude oil can be found based on time after the spill and for different environmental conditions.

$$V_{oil} = 1 - PE \tag{9}$$

The final equation for calculating the residual oil volume is:

$$V_r = A * \frac{\bar{h}}{1000} - S * v * h * 0.06 * TE * (1 - PE) * t_{operation} * 0.5 \tag{10}$$

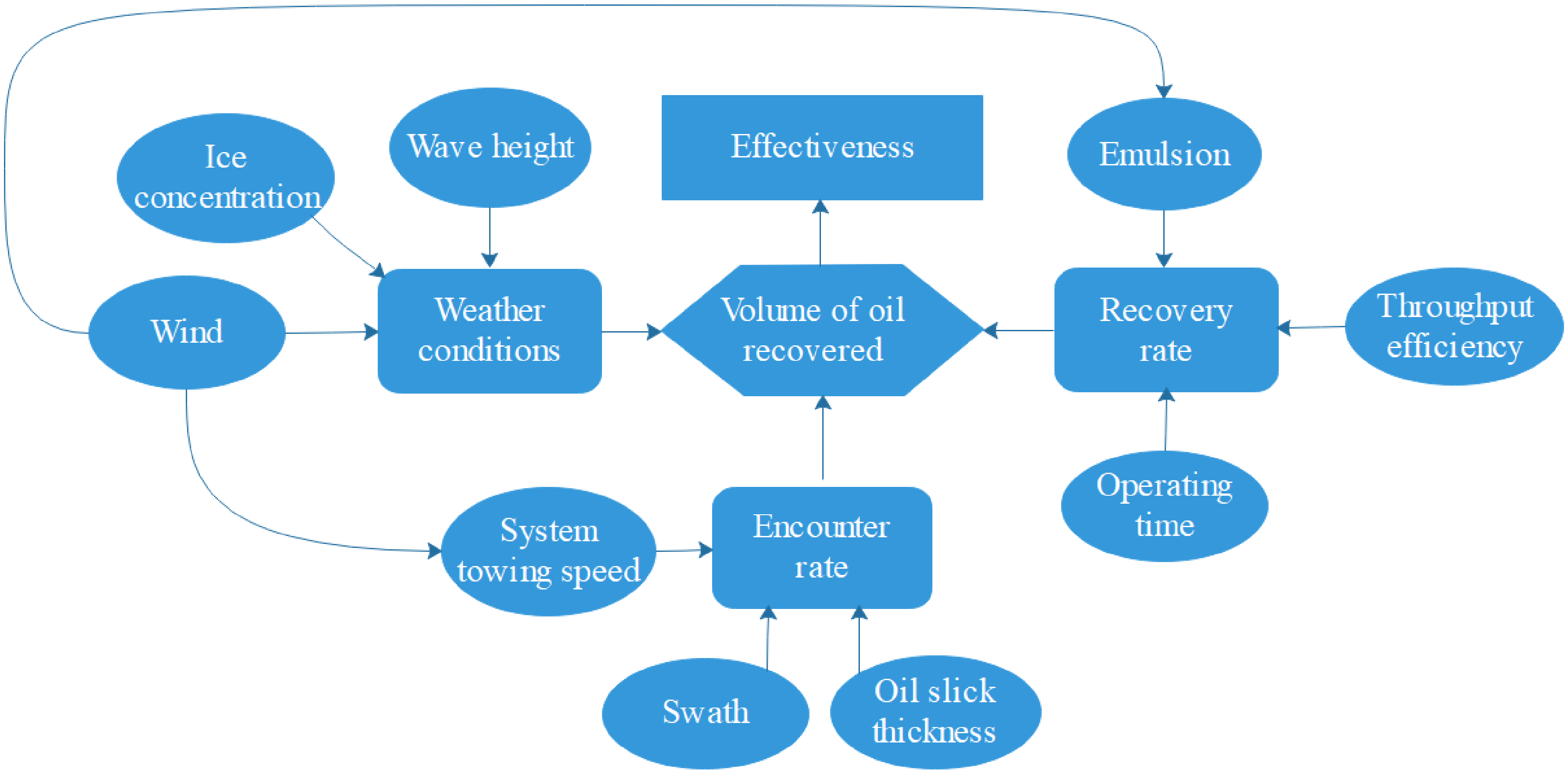


Figure 4.4 Influence diagram illustrating the main factors affecting the effectiveness of mechanical recovery.

4.1.2 *In situ* burning

The procedure for *in situ* burning consists of containing, heating, and igniting the spilled oil, sustain and monitor the burn, and in the end, recover the burn residue. There are different strategies for how to conduct an *in situ* burn. As with mechanical recovery, the containment and burning of the oil can either be done simultaneously or consecutively. Effectiveness of both strategies are discussed in this thesis. An oil slick can also be burned without containment if the slick is thick enough. However, the spill has often spread out by the time a response team reaches the location or environmental conditions make uncontained burning hazardous. To ignite the oil, pre-heating is sometimes required to produce a sufficient amount of ignitable vapour. If there is no risk that the oil will ignite too early, while it is still near the boats, the ongoing burn can continuously be fed by more oil. This is the case with heavy and emulsified oil [68].

Over time, the lighter, volatile compounds are transported to the atmosphere through evaporation, while the heavier compounds remain in the oil slick. Between 20 and 50 % of the crude oil may evaporate, most of it during the first few days after a spill. Higher degree of weathering makes the oil harder to ignite as it contains less volatile compounds. Evaporation of lighter compounds also makes the remaining oil more viscous. Higher viscosity enhances the conditions required for emulsions to form. Oils with more than 50 % emulsions will require more heating to break the water droplets. Stable oil emulsions are the hardest to ignite and might require the addition of a primer. A primer is often used to assist the ignition of heavy or weathered oil. The oil is then soaked with either diesel fuel or kerosene a few minutes before applying an igniter. Tests have shown that once the oil is ignited, the heat will break down the emulsions, allowing the burn to continue [38].

A slick will stop burning when there is not enough vapour. Amount of vapour produced during the burn depends on the slick thickness, concentration of volatiles in the oil, and amount of heat radiated back to the oil slick. The slick thickness should be at least between 0.5 to 3 mm for the required heat transfer to take place. If the slick is thinner, heat will be lost to the water below the oil slick, which will result in a decrease in temperature and a lower production of vapour [38].

The effectiveness of *in situ* burning depends on several factors: the slick thickness, composition of the oil, area of the oil slick, and the degree of weathering are just a few of them. The burn effectiveness can, in a similar way to mechanical recovery, be determined by comparing the volume of oil burned, V_b (m^3), to the initial oil volume spilled, V_i, (m^3).

Several factors must be considered when trying to determine the effectiveness of *in situ* burning. Figure 4.5 is an influence diagram illustrating the main factors and their dependencies that must be considered in an effectiveness model. Based on this diagram, another model has been established. The residual oil volume, V_r (m^3), is the difference between the initial oil volume and the volume of oil burned. V_i is calculated in the same way as in Chapter 4.1.1, using Equation 5.

$$V_r = V_i - V_b \tag{11}$$

4.1.2.1 Containing and burning

If containment and burning are done separately, the volume of burned oil can be calculated by adding the time required for each step in the process and determine how many cycles that can be conducted within the operation time. The first step is to contain oil to maximum capacity of the boom, C_{max} (m^3), which is 1/3 of the boom area, A_{boom} (m^2), and 1/3 of the draft length, D (m) C_{max} is calculated using Equation 12. The area of the boom can be calculated based on the length of the boom, L (m), using a parabolic equation, but is in Equation 13, for simplicity reasons, based on an equation obtained from BSEE and Genwest Systems [65].

$$C_{max} = \frac{1}{3} A_{boom} * \frac{1}{3} D \tag{12}$$

$$C_{max} = (0.0275 * L^2) * \frac{1}{3} D \tag{13}$$

The time required to fill the boom, t_{max} (min) depends on C_{max} and ER. The ER is calculated using Equation 7.

$$t_{max} = \frac{C_{max}}{S * v * h * 0.06} \tag{14}$$

The second step is an optional safety measure, where the filled boom is towed 300 to 600 m away from the remaining slick before igniting. The third step is to burn the contained oil. The time required to burn C_{max}, t_{burn} (min), is calculated based on D and the burn rate, B (mm/min).

$$t_{burn} = \frac{D}{0.003 * B} \tag{15}$$

The time required to seal the boom and ignite the oil is negligible compared to the total operation time [54]. Once the oil is ignited, the burn rate depends on the oil's characteristics and properties such as viscosity and percentage of water-in-oil emulsion. The initial reservoir characteristics of the oil are known but will change as the oil weathers. For oils where weathering studies are conducted, the initial characteristics and changes happening to the oil over time will be known to a certain extent. Based on this information, the burn rate can be determined. How fast the weathering occurs, depends on environmental conditions such as wind speed and temperature. Tests have uncovered the fact that the burn rate does not vary significantly with different types of crude oils and with degree of weathering [38]. Typical rates and additional information about various crude oils are presented in Table 4.1. If the oil slick is thick enough and there are sufficient concentrations of volatile compounds to produce vapour, the oil will normally burn once it is ignited.

Table 4.1 Burning properties of various crude oils [38].

Fuel	Burnability	Ease of ignition	Flame spread	Burning rate (mm/min)	Efficiency range (%)
Light crude	High	Easy	Moderate to high	3,5	85 – 98
Medium crude	Moderate	Easy	Moderate	3,5	80 – 95
Heavy crude	Moderate	Medium	Moderate	3	75 – 90
Weathered crude	Moderate	Add primer	Slow	2,5 – 3	60 – 90
Crude oil with ice	Low	Difficult, add primer	Slow	2	50 – 90
Emulsified oil	Low	Add primer	Slow	2 – 3	30 – 70

The fifth and final step is to collect the burn residue. BSEE and Genwest Systems suggest one hour for this step [65]. No recovery methods are capable of recovering the entire volume of residue. Some residue may sink or adhere to equipment, or the slick may be too thin to be recovered. Sometimes the residue is not recovered, but left behind to be broken down biologically [38].

The total number of cycles, NC, possible during the operation time will be:

$$NC = \frac{t_{operation}}{t_{max} + 2 * t_{offset} + t_{burn} + t_{residue}} \tag{16}$$

The volume of oil burned will be dependent on NC and C_{max}. The residual oil volume can, based on these equations, be calculated:

$$V_r = A * \frac{h}{1000} - C_{max} * NC \tag{17}$$

4.1.2.2 Feeding an ongoing burn

To calculate the volume of burned oil in the case of feeding an ongoing burn it is assumed that the burn volume is lower than the encounter volume. The burn volume will then be the limiting factor and can be calculated by multiplying A_{boom} with the thickness reduction and n number of successful burns. The reduction depends on B and the duration, t (min), of the burn.

$$V_b = A_{boom} * \frac{B}{1000} * t * n \tag{18}$$

The final equation for calculating residual oil volume is:

$$V_r = A_{spill} * \frac{h}{1000} - (0.0275 * L^2) * \frac{B}{1000} * t * n \tag{19}$$

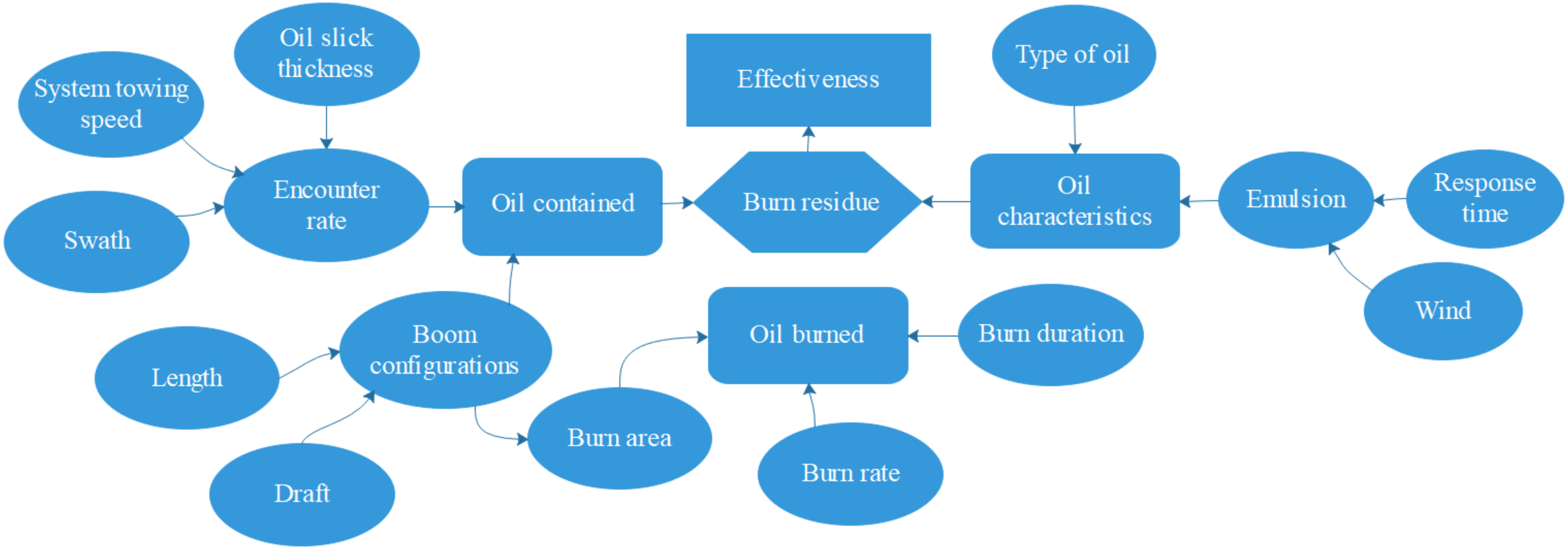


Figure 4.5 Influence diagram illustrating the main factors affecting the effectiveness of in situ burning.

4.1.3 Chemical dispersants

As with the previously discussed response methods, effectiveness of dispersants also depends on a variety of factors. The most important factor is the oil composition, followed by sea energy and amount of chemicals applied [27]. Other factors that influence is the type of chemical applied, degree of weathering, and temperature. The influence diagram in Figure 4.7 illustrates these factors and their dependencies.

According to Fingas, the concentration of saturates is highly important in relation to the oil composition [27]. Oils consisting mostly of saturates will easily disperse, whereas oils containing resins, asphaltenes, or waxes are harder to disperse. Oils containing these heavier compounds are often more viscous, but viscosity alone should not be considered a determining factor in this case [27, 34]. Still, viscosity is frequently used as a cut-off value to say whether the oil is dispersible or not [34, 46]. Scientists have also found a correlation between effectiveness of dispersants and the carbon number, showing that small n-alkanes up to C20 are likely to disperse while larger n-alkanes resist dispersion [27].

The sea water temperature affects how the oil will spread and disperse. In lower ambient temperatures, the oil will act less like a fluid and more like a semi-solid mass. The surface tension of the oil slick will then not allow dispersants to penetrate and the mechanical resistance will be too great for droplets to form. Dispersion effectiveness is also dependent on the size of the droplets formed during dispersion and the turbulence energy in the water column. Oil droplets may form in a wide range of sizes, but should be between 1 µm to 70 µm for the method to be effective and smaller than 45 µm to be stable. According to Figure 4.6, the application of a dispersant increases the number of stable droplets significantly. The method is also dependent on sufficient turbulence to keep the droplets suspended in the water column. [46].

The effectiveness of dispersants can simply be defined as the ratio between the volume of oil that the dispersant disperses into the water column to the volume of oil remaining at the surface. However, these values are hard to retrieve as there is no sufficient method for determining the concentration of oil dispersed.

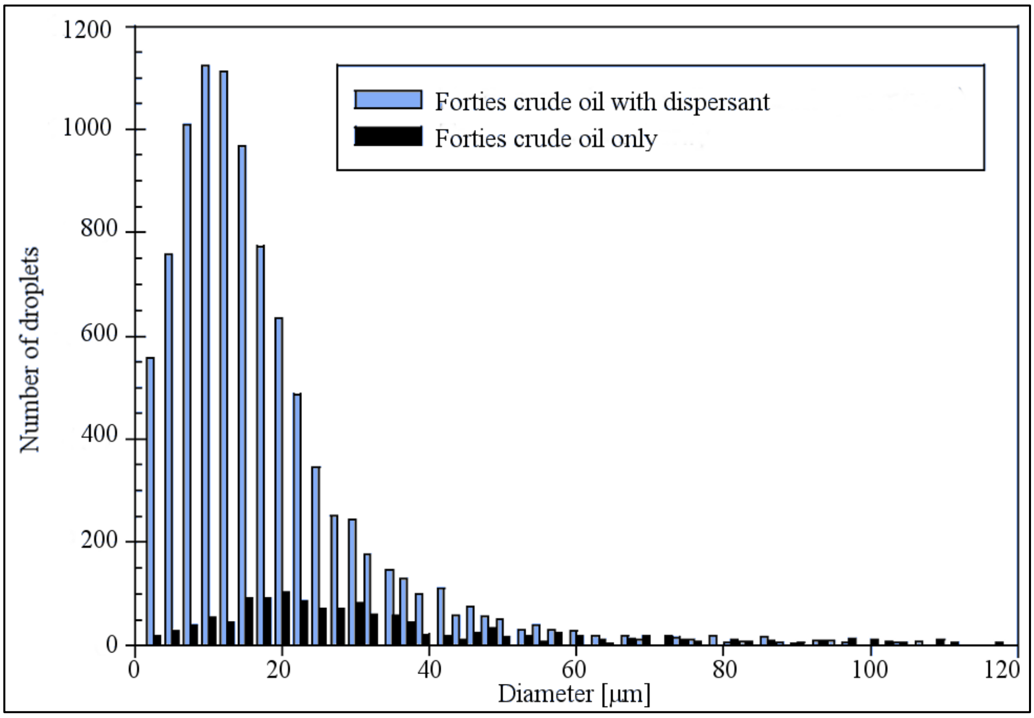


Figure 4.6 The effect of chemical dispersant (Dasic Slickgone NS) on droplet size distribution (Figure modified from Coolbaugh and McElroy [42]).

Fingas states that all methods measuring the dispersant effectiveness must determine the mass balance to be valid [27]. In wave-tank tests where the mass balances were determined, they could only account for 50 to 75 % of the oil. Oil that is unaccounted for can be misinterpreted as oil dispersed by the dispersant, which results in an overestimation of the effectiveness. The lack of a mass balance can overestimate the effectiveness by a factor from 1 to 8 times [27]. Even though today's laboratory tests provide sufficient estimates of the effectiveness, few of the methods developed so far give good representations of the actual field conditions [27]. It is difficult to replicate conditions such as waves, currents, microorganism activity etc. Even in large wave-tanks the oil will to some extent be contained which will affect the outcome.

Different methods have been developed in an attempt to determine the mass balance and one of the preferred methods for determining oil concentration in the water column is fluorometric measurements. In the field a fluorometer is towed behind a boat at least 1 m below the oil slick to measure the "real time" oil concentration in the water column [46]. A fluorometer sends out UV or near UV rays to activate the aromatic species in the oil. However, this method is quantitatively unreliable as the fluorometer only measures aromatics with two to five rings. Neither does it distinguish between dispersed and dissolved oil. As the oil weathers, the composition changes and the concentration of aromatics increases. The fluorometer will therefore measure a higher concentration of aromatics later in the experiment, without a larger volume of oil needed to be dispersed [27]. Because of these changes, the method must include time as a parameter. Even then, the sources of errors are multiple and the method should be used in combination with visual observation.

Coolbaugh and McElroy states that the total effectiveness of chemical dispersants can be divided into three components: operational effectiveness, chemical effectiveness, and hydrodynamic effectiveness [42]. Operational effectiveness describes the encounter rate of different application methods, such as spraying from airplanes and boasts, and how well the slick is targeted and the dispersant incorporated into the oil. Chemical effectiveness describes how much of the treated oil that will form stable oil droplets in the water column. Hydrodynamic effectiveness describes the transport of the dispersed oil and the degree of dilution and mixing in the water column due to turbulence. Only the chemical effectiveness can be properly assessed in the laboratory using wave tanks, but fails to establish a mass balance as previously discussed.

Most quantitative models focus on the operational effectiveness. This includes the logistics and how large area that can be covered and treated [69, 70]. They do not include how well the treatment works. Today, many monitoring protocols instead focus on determining whether or not the application of dispersants have any effect at all, rather than trying to quantify the degree of effectiveness. A quantitative model to determine the effectiveness of dispersants was neither in this thesis successfully established due to lack of understanding on the physical and chemical aspects of the method. Instead, three groups of effectiveness, presented in Table 4.2, have been suggested based on the discussed factors. The category boundaries should not be considered as cut-off values and oils may be dispersible beyond the given boundary for ineffectiveness. The table is only a guideline and each case must be considered individually.

Table 4.2 Categories of chemical dispersion effectiveness. Values are collected from various sources [17, 46, 71].

	Highly effective	Somewhat effective	Ineffective
API	17 - 45		< 17
Viscosity [cSt]	< 5000	5000 – 10,000	> 10,000
Temperature [◦C]	> pour point	< pour point	>15 below pour point
Droplet size [μm]	< 45	45 – 70	> 70

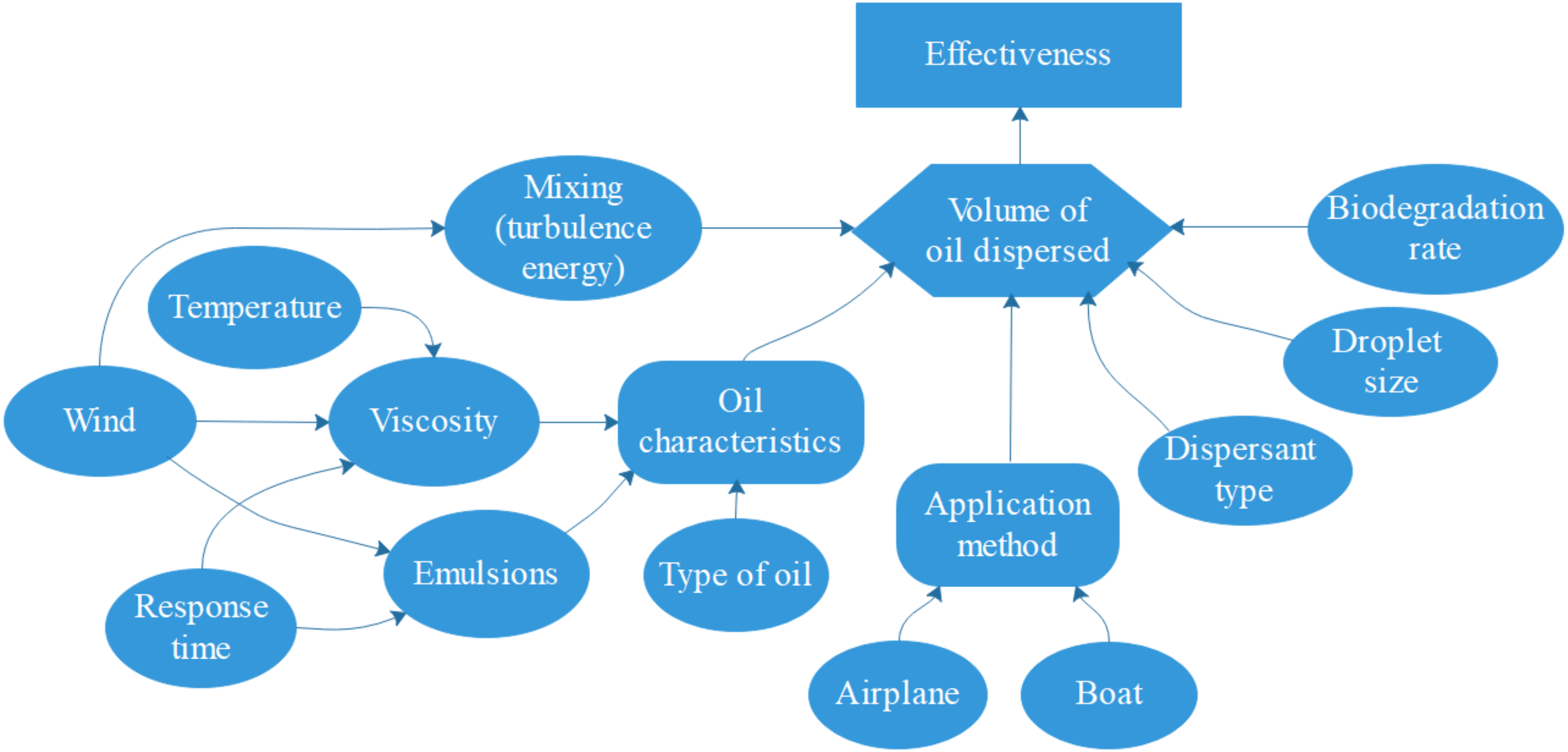


Figure 4.7 Influence diagram illustrating the main factors affecting the effectiveness of chemical dispersants.

4.1.4 Uncertainties

Uncertainty is often used to describe the lack of knowledge or information. To decrease the uncertainty in the effectiveness models, more knowledge and information are needed on the factors illustrated in the influence diagrams. Several factors are decision variables that can be controlled by the response team, such as the swath, towing speed, and operation time. Other factors, such as weather conditions, response time, and equipment characteristics, can be quantitatively determined using developed methods.

Oil characteristics are harder to determine and will change over time during the response operation. However, much knowledge has been obtained through weathering studies which provides a good lead to what should be expected in the field. Frequent sampling of the oil throughout the operation will further improve the accuracy of these input values.

One common factor in all effectiveness models, that has proven to be much harder to measure, is the oil slick thickness. It is needed both to determine the initial volume of oil spilled, the volume of the oil contained by the booms, and the residual volume of oil. By being able to measure the thickness with less uncertainty, researchers will be able to create more accurate models and the response systems can be more efficiently deployed. If the thickness distribution in a slick is known, the response team can determine the ideal thickness for the system and use a measuring tool to target or obtain it. So far, the methods developed can only give estimates with poor accuracy, seeing that the slick will not spread homogenously, but tend to form in a concave or convex shape with patches and windrows of varying thicknesses. Still, it is widely accepted to use an average value of oil slick thickness [66, 67, 72].

The thickness and spreading of the oil are affected by environmental conditions such as wind and waves. The spilled oil often forms windrows, oil concentrated in thicker bands parallel to the wind direction. The oil properties and degree of weathering, such as viscosity and emulsion percentage, may also have an impact. Low viscosity oils quickly spread out to a thin layer, whereas higher viscosity oils will have a greater spatial variation in thickness [67].

To measure the spilled volume the BAOAC, a method that uses visual analysis to convert observed colours of the oil slick to thicknesses, is often used [67]. Table 4.3 shows the codes that are used in the method. It cannot be used to determine the thickness of contained oil, because it is not possible to estimate thicknesses above 200 µm by visual analysis. Other methods use infrared images to measure the amount of thermal energy that is reemitted from the solar energy absorbed by the oil. Thick oil slicks reemit much energy and appear hot, medium oil slicks reemits some energy and appear cold, whereas thin oil slicks are not detected. The method has a minimum detection thickness between 10 and 70 µm [73].

Table 4.3 Colours used to visually estimate the thickness [µm] and volume of oil slicks based on the BAOAC [5].

Code	Appearance	Layer thickness interval [µm]	L/km^2
1	Sheen (silvery/grey)	0.04 - 0.3	40 - 300
2	Rainbow	0.3 - 5.0	300 – 5000
3	Metallic	5.0 - 50	5000 – 50,000
4	Discontinuous true oil colour	50 - 200	50,000 – 200,000
5	Continuous true oil colour	> 200	> 200,000

Allen et al. simulated multiple oil spills of different oil types under various wind and temperature conditions [74]. Based on the results they suggested nominal average oil thicknesses of 2.54 mm, 1.27 mm, and 0.64 mm for days 1 to 3. The computer simulated batch spills, one-time releases, but the thicknesses are also representable for continuous spills. A continuous release can in a simplified way be compared to a series of individual batch releases.

Figure 4.8, Figure 4.9 and Figure 4.10 show the changes in oil slick thicknesses for batch spills with volumes of 500,000 bbl. Data are obtained from the report of Allen et al. and presented in Appendix 3 [74]. The boxes represent the middle 50 % of the data, the mid-lines represent the medians, the mid-points represent the mean values, while the whiskers represent the values outside the middle 50 %. Figure 4.8 shows the thickness of Light Louisiana Sweet crude oil (LLS), a light oil with an API gravity of 38.5. Figure 4.9 shows the thickness of Alaska North Slope crude oil (ANS), a medium crude oil with an API gravity of 29.6. Figure 4.10 shows the thickness of IFO300, a heavy crude oil with an API gravity of 11.9. The statistical data are presented in Table 4.4.

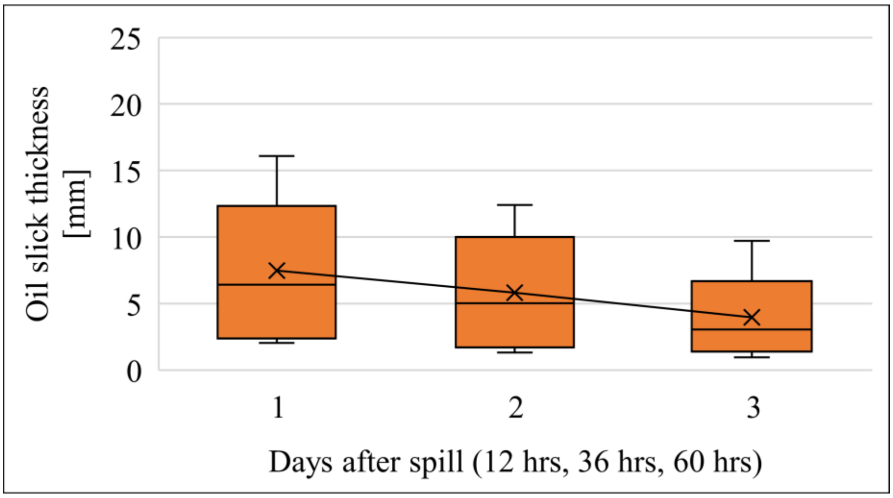


Figure 4.8 Box plot of oil slick thickness over three days for Light Louisiana Sweet.

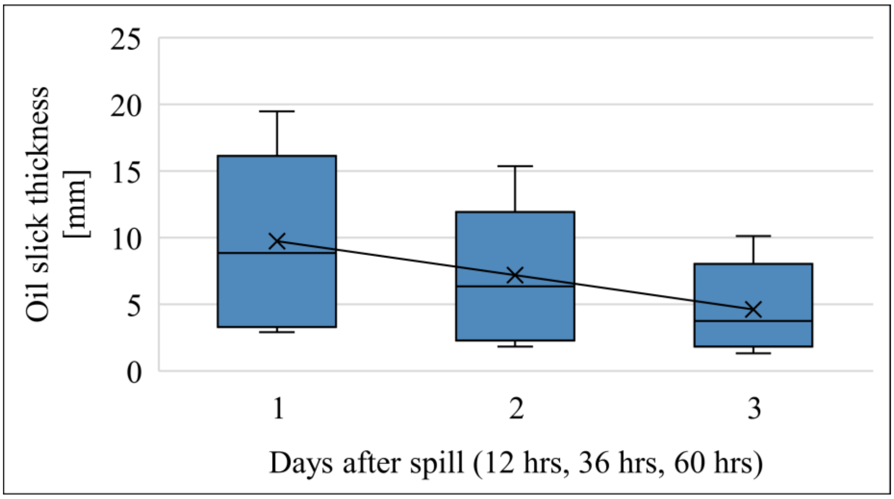


Figure 4.9 Box plot of oil slick thickness over three days for Alaska North Slope.

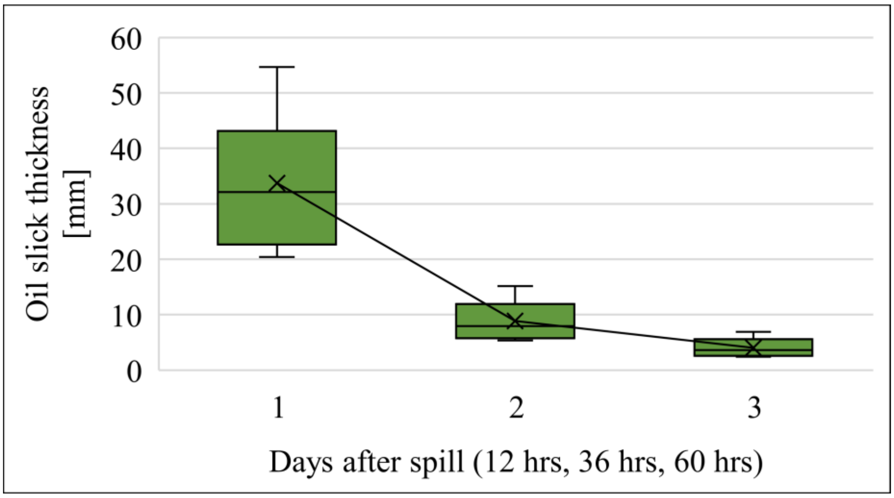


Figure 4.10 Box plot of oil slick thickness over three days for IFO300.

The box plots become shorter for each day, meaning that the spread of the data and the uncertainty of the thickness decrease, which is confirmed by the calculated standard errors (SE). The medians are smaller than the means, indicating that the distribution is positively skewed. That is, that the data are concentrated in the lower parts of the diagram while a few large values drive the mean upward, hence the longer upper whisker.

Table 4.4 Statistical data of oil slick thickness [mm] distribution for Light Louisiana Sweet, Alaska North Slope and IFO300 over a 3-day period.

	Day	Min	Max	Median	Mean	SD	SE
LLS	1	2.03	16.08	6.41	7.48	6.47	1.87
	2	1.31	12.41	5.02	5.81	5.03	1.45
	3	0.97	9.70	3.06	3.96	3.14	0.91
ANS	1	2.90	19.46	8.83	9.73	5.19	1.50
	2	1.82	15.35	6.33	7.17	4.19	1.21
	3	1.31	10.10	3.74	4.61	2.90	0.84
IFO300	1	20.42	54.69	32.13	33.73	10.94	3.16
	2	5.32	15.13	7.96	8.85	3.25	0.94
	3	2.38	6.91	3.58	4.02	1.54	0.44

The oil slick thicknesses vary to a great extent, from a maximum thickness of 54.69 mm to a minimum thickness of 0.97 mm. The SEs range from 0.44 to 3.16 mm. The thicknesses of all three types of crude oils vary, but it is apparent that heavy oils have the greatest variation and the largest uncertainty.

The mean values calculated in this thesis are higher than the nominal average oil thicknesses suggested by Allen et al. A reason for this can be that the calculations done in the thesis only use data from simulations of the largest oil release of 500,000 bbl, while Allen et al. use data from simulations of oil spills with spill volumes varying from 500 to 500,000 bbl. It should also be noted that all minimum thicknesses were achieved at 15 °C and all maximum thicknesses at 0 °C. As the viscosity of an oil depends on the temperature, it can be that the lower temperatures reduce the viscosity and therefore also the spreading and thinning of the slick.

The calculated means show that both light and medium crude oils will form thin slicks around 9 mm before they thin and spread out to around 4 mm within 3 days. Whereas heavier crude oils may form oil slicks with thicknesses varying between 20 and 55 mm with a mean around 34 mm. After 3 days, also this oil slick will have a thickness around 4 mm.

The methods mentioned above can provide good estimates of the thicknesses that can be further used to calculate the volumes of spilled oil. However, they are difficult to use to determine the thickness of the contained oil and the residue, especially after *in situ* burning where there are great changes in the oil properties. Because the thickness value is of such great importance for creating effectiveness models of higher accuracy, there has been much focus on developing new technology to be able to quantitatively determine the thickness. As a result, two new sensors, the Capacitive sensor and the Spectro sensor, have been developed. These tools measure the thickness of the slick and communicates the values in near real-time. The first mentioned is made to measure thicknesses above 3 mm while the latter will measure thicknesses below 3 mm. They can be handheld or attached to booms or skimmers during an operation. The Capacitive sensor measures the capacitance of the air, oil and water that it is in contact with and uses this data to estimate the oil-air and oil-water interfaces. The Spectro sensor measures the light absorption using LED-based spectrometry [75]. The performance in harsh weather must be improved and there are issues related to oil-fouling of the sensor lenses, affecting the accuracy [76]. Some changes and enhancements are still needed, but the equipment shows the important progress that is done within the field.

4.1.5 Comparison to existing models

The models developed in this thesis were compared to the Estimated Recovery System Potential (ERSP) and Estimated Burn System Potential (EBSP) calculators, developed by BSEE and Genwest Systems, to check the liability [65, 66]. The volumes of oil recovered and burned during simulations of a continuous oil spill have been calculated and presented in the ERSP and EBSP user manuals. In order to get comparable results, the same values used by BSEE and Genwest Systems were used as input values in the models developed in this thesis. The results from the different methods are presented in Table 4.5. The values calculated are the volumes recovered by one system operating for 12 hours. The EBSP calculator is not adapted to the strategy of feeding an ongoing burn, and no other models for this strategy were found.

Table 4.5 Calculated volumes of oil recovered or burned during an oil spill response scenario of a continuous oil spill.

Response system	Volume recovered/burned ERSP/EBSP models	Volume recovered/burned Models from thesis
Mechanical recovery	344 m^3 (2166 bbl)	374 m^3 (2352 bbl)
In situ burning (containment and burning)	346 m^3 (2177 bbl)	336 m^3 (2113 bbl)
In situ burning (feeding an ongoing spill)	-	526 m^3 (3308 bbl)

4.2 Case study

In order to determine the effectiveness of a response system and the potential impact on the ecosystem, a comparison must be done between the results of doing nothing and the results of implementing a recovery system. Using the models derived in Chapter 4, the volume of oil on the surface after 10 days of cleaning have been compared for the various cases, and their relationship to the environmental impact is discussed.

4.2.1 Case area

In this case study the Johan Castberg field and production licence PL532 is chosen as the case area. This is one of the newest fields in development in the Barents Sea. Statoil, the operator of the field, handed in the Plan for Development and Operation (PDO) for the subsea installation to the government late in 2017. Drilling is planned to start in the end of 2019 while production is expected to begin in 2022. The field is located approximately 100 km northwest of the Snøhvit field and 150 km northwest of the Goliat field. The nearest point to the mainland, Ingøy, is 200 km away while Bjørnøya is 210 km away [77].

The Johan Castberg field consists of three reservoirs, each with a different type of oil. Skrugard crude oil has the longest degradation time out of the three and is therefore chosen as reference oil. It is a naphthenic oil with a density of 0.871 g/ml which forms stable emulsions. The scenario considered in this case is an uncontrolled release of oil as a result of a subsea blowout during production drilling (defined situation of hazard and accident (DSHA) 1 from PDO II) [77]. The reason for choosing this scenario is that it is the scenario with the greatest consequences. In the unfortunate case of an acute oil spill during drilling, the weighted spill rate is estimated to be 8100 m^3/day and weighted duration is 15.8 days. The worst case scenario is a spill rate of 10,000 m^3/ day lasting for 70 days [77]. Oil drift analyses have been performed using the OSCAR model to estimate how the oil will spread over time. In such an analysis, the area of impact is defined by grid cells of 10x10 km where there is 5 % chance or more that the volume of oil will exceed one ton.

The Johan Castberg field is located in the southwestern part of the Barents Sea ecosystem which is characterised by an influx of temperate water from the Atlantic Ocean. There are no valuable or vulnerable areas in the vicinity of the field, but it is a key area for seabirds such as the common guillemot and Atlantic puffin.

4.2.2 Estimated response time

The nearest standby oil spill response system, the oil recovery vessel Esvagt Aurora, is located 150 km away, near the Goliat field. The vessel is equipped with both mechanical recovery systems and dispersion systems. It can be made available within 4 hours and will spend approximately 5.8 hours to the Johan Castberg field, with a top speed of 14 knots. After arriving at the location, one hour must be expected to deploy either the mechanical recovery or chemical dispersant system. The total time required from the response unit receives the notification until they are set up at the location is estimated to 10.8 hours.

Besides the standby system on the Goliat field, there is a NOFO base located in Hammerfest, 240 km away. From there, the vessel Island Contender and a response unit require up to 10 hours to mobilize, 9.3 hours to reach the scene and 1 hour to deploy the equipment. The mobilizable fleet requires up to 20 hours from Hammerfest to the Johan Castberg field from the time that they receive the notification until they are set up at the location [51].

The nearest dispersant airplane is a Boeing 727 provided by Oil Spill Response Limited (OSRL), located at the Robin Hood Airport in Doncaster, UK. The system is ready to mobilize within 4 hours, fuelled and loaded with dispersant. From its location in the UK the travel time is about 5 hours with a transit speed of 250 knots [78]. The total time needed from notification to the first round of dispersant application is then 9 hours. The nearest airport with a sufficiently long landing strip is the Tromsø Airport, 320 km away. The transit time from here to the field, after refuelling and reloading, is about 40 minutes. Helicopters are also often used to apply dispersants, however, the distance between the depot and the spill location should not exceed 50 km.

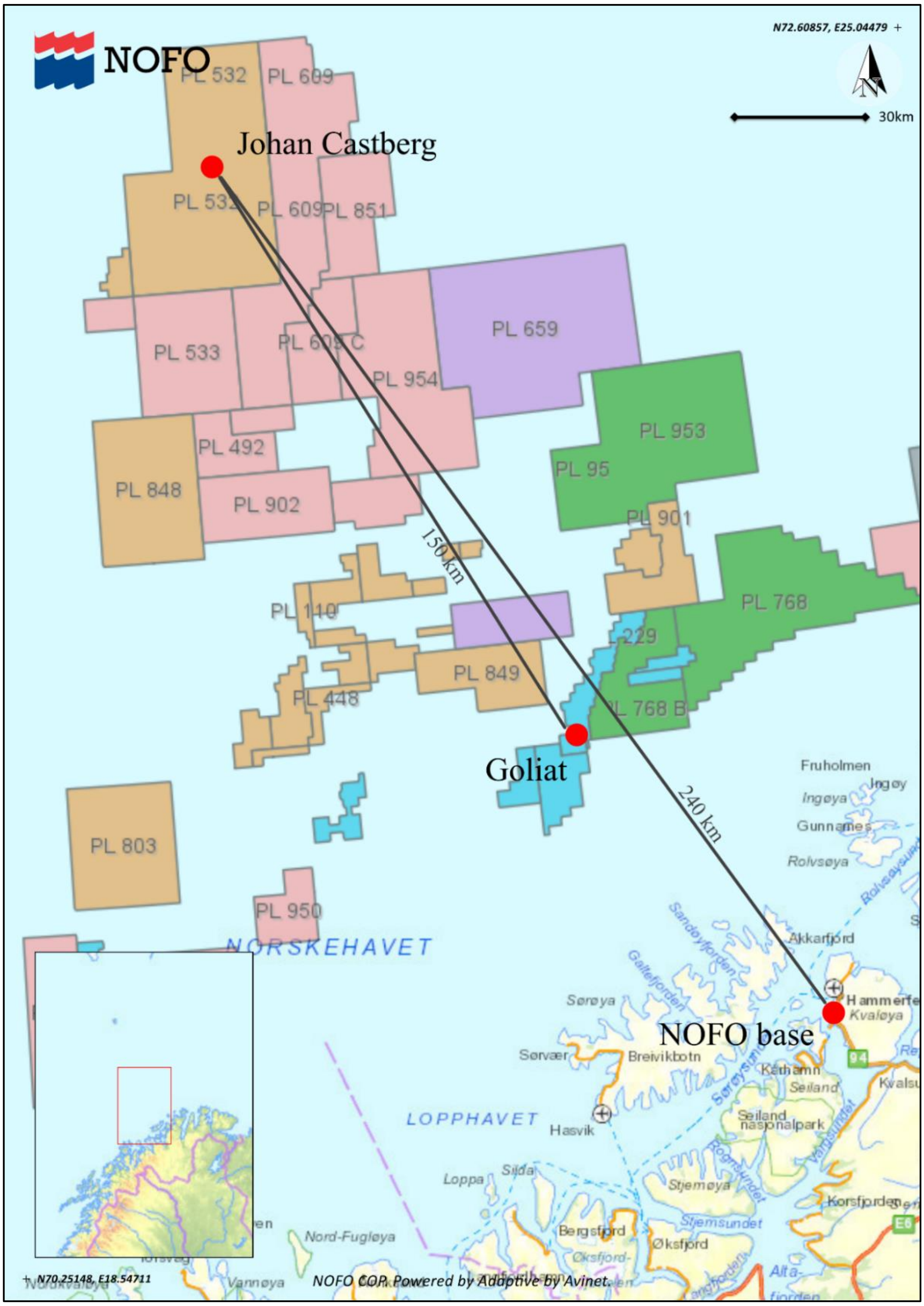


Figure 4.11 Map showing distances between the case area and response equipment. The closest response system is the standby team on the Goliat field, 150 km away, while the closest NOFO base is located in Hammerfest, 240 km away. The base map of the figure is collected from NOFO's web map solution NOFO COP OSP [79].

4.2.3 Case 0 – No response

Case 0 is the case of an acute oil spill with no response system implemented. If a worst-case scenario was to happen, a volume of 10,000 m^3 of oil would be spilled into the marine environment and could possibly last for as long as 70 days. Simulations of a case like this shows that the probability for the oil to reach shore is 21 to 23 %, depending on the season. The coast of Finnmark has a higher risk of being impacted than Bjørnøya, due to the wind directions and ocean currents. The shortest time needed for the oil to reach Finnmark is 20 to 26 days, whereas it will take as much as 90 days to reach Bjørnøya. If the spill occurs in summer (April to June), 6546 tons of oil can possibly reach the coast, while in winter (October to December) the volume is estimated to be about 1011 tons of oil. The potential influence area is presented in Figure 4.12. Fortunately, the probability for an event of this extent to occur is estimated to be once every 350,000 year per well [77].

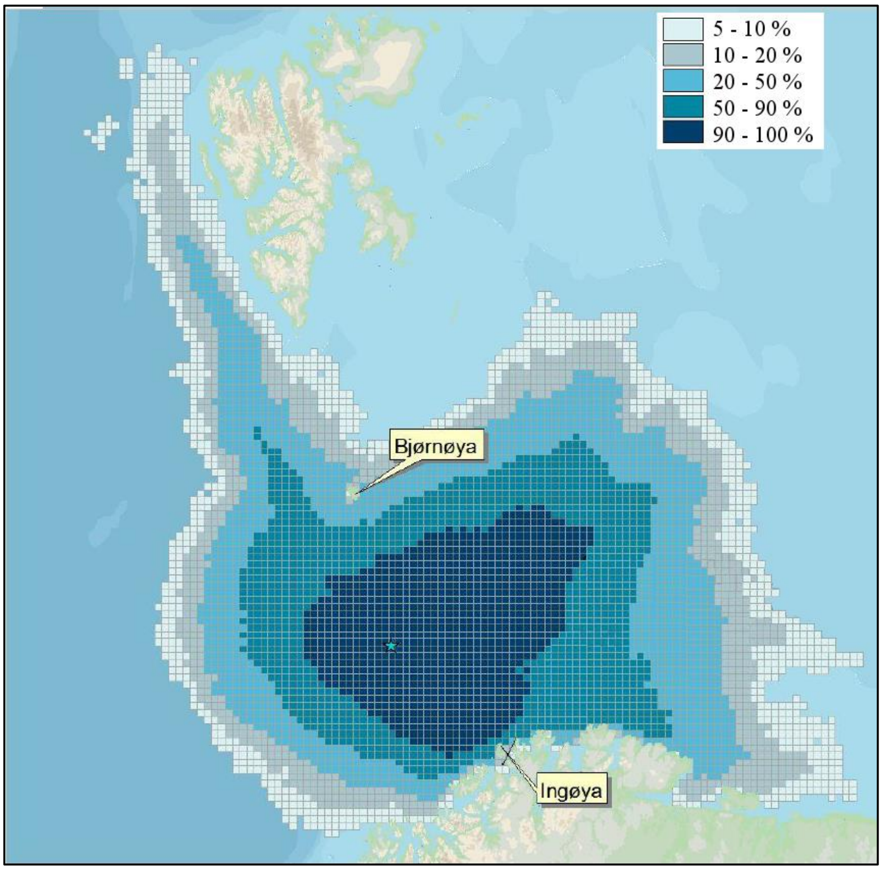


Figure 4.12 Potential influence area from an oil spill (DSHA 1) of 10,000 m3/day, lasting for 70 days. The colours represent the probability of more than 1 ton of oil present in the 10x10 km grid cells. The figure is a statistical presentation of the influence area based on multiple simulations and should not be interpreted as one single oil spill scenario [80].

According to one of the OSCAR simulations, the oil slick will cover an area of 7500 km^2 after 10 days if no response is implemented (Figure 4.13). A volume of 147,704 tons of oil, approximately 172,500 m^3 oil, will be floating on top of the water surface with an average thickness of 0.023 mm. The thickness is expected to deviate greatly from this value, as it includes everything from the thickest accumulations of the oil to the thinnest oil sheens.

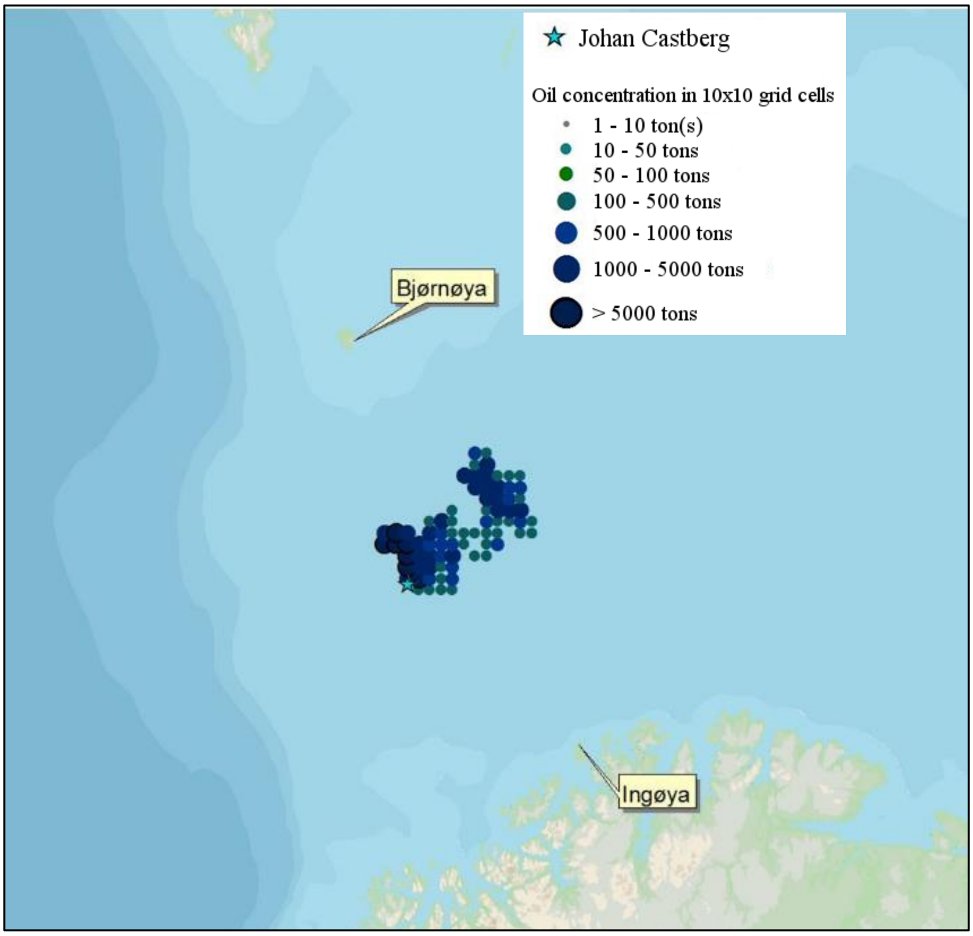


Figure 4.13 Simulation of spreading of oil after 10 days for case 0 of the DSHA 1 scenario. The oil covers an area of 75 grid cells, with an average oil volume of 1969 tons in each. Each cell is 10x10 km in size [80].

Natural weathering will still account for some removal of oil from the water surface. According to the weathering study on Skrugard oil, after two days in wind speeds above 15 m/s, no oil will exist on the water surface (Figure 2.7). About 80 % of the oil will have naturally dispersed and 20 % evaporated. However, if the wind is below 2 m/s, close to 0 % will disperse and only 13 % will evaporate. It is obvious that during a response gap, the level of ecosystem risk highly depends on the environmental conditions during that time.

4.2.4 Case 1 – Mechanical recovery

Case 1 is the case where mechanical recovery is implemented as a response method lasting for 10 days. The input value for the area is set to be the same as the area of the slick after 10 days, as shown in Figure 4.13. The area is 7500 km^2 with an average thickness of 0.023 mm. The skimmer will approach the thicker areas of the slick and an average thickness will in this case result in an underestimation of the encountered volume. Instead, a thickness of 2.54 mm, as suggested by Allen et al., is used to calculate the ER during all 10 days, as it is a continuous spill. According to NOROG, the swath of a NOFO system in open ocean can be 200 m with a towing speed of 0.4 m/s (0.75 knots), but these are decisions variables that must be made according to the operating conditions [52]. A NOFO system includes 400 m of booms [20]. Based on the recommendations to use a swath width of 1/3 of the boom length, the width used in this case will then be around 135 m. The TE is set to 75 %, as this is the recommended value when no specific skimmer type is defined [66]. From Figure 2.8, the PE for Skrugard oil can be determined based on the response time. For most environmental conditions, the PE will be anywhere between 30 and 80 % by the time recovery starts. The mean value of 55 % is used in this case. The operation is set to last for 10 days with 5 active skimmer systems. Using Equation 10, the residual oil volume is in this case calculated to be:

$$V_r = 7.5E9 * \frac{0.023}{1000} - 135 * 0.4 * 2.54 * 0.06 * 0.75 * (1 - 0.55) * 12 * 60 * 0.5 * 10 * 5$$

$$V_r = 172\,500 - 49\,995 = 122\,505\ m^3$$

By implementing one mechanical recovery system for 10 days, 49 995 m^3 of oil will be recovered and the remaining oil slick volume will be 122 505 m^3, constituting for a 29 % reduction.

4.2.5 Case 2 – *In situ* burning

4.2.5.1 Containing and burning

The same input values used in chapter 4.2.4 for the initial volume are used in this case. The measurements of the Pyroboom, one of the boom types used during the DWH response, are used as input values. The boom length is 150 m with a 0.5 m draft [38]. It should be noticed that the recommended minimum draft in open water is 0.66 m (26 in) according to ASTM standards [65]. The same oil slick thickness of 2.54 mm is used, and the swath is assumed to be 50 m with a tow speed of 0.4 m/s. The C_{max} and t_{max} are calculated using Equations 13 and 14:

$$C_{max} = (0.0275 * 150^2) * \frac{1}{3} 0.5 = 103\ m^3$$

$$t_{max} = \frac{103}{50 * 0.4 * 2.54 * 0.06} = 34\ min$$

The slick is towed 300 m away from the remaining oil slick. The offset time will then be:

$$t_{offset} = \frac{300}{0.4 * 60} = 12.5\ min$$

The time to burn the contained oil is calculated using Equation 15. The burn rate is with reference to Table 4.1 assumed to be 2 mm/min since the oil will be emulsified.

$$t_{burn} = \frac{0.5}{0.003 * 2} = 83\ min$$

The operating time is set to be 12 hours for 10 days with 5 burn teams. The total number of cycles and the residual oil volume are then calculated using Equations 16 and 17:

$$NC = \frac{12 * 60}{34 + 2 * 12.5 + 83 + 60} = 3.54$$

$$V_r = 7.5E9 * \frac{0.023}{1000} - 103 * 4 * 10 * 5$$

$$V_r = 172\ 500 - 20\ 600 = 151\ 900\ m^3$$

By implementing one *in situ* burning system where containing and burning are done separately for 10 days, 20 600 m^3 of oil will be recovered and the remaining oil slick volume will be 151 900 m^3, constituting for a 12 % reduction.

4.2.5.2 Feeding an ongoing burn

Based on the response time in this case study, the oil is expected to have weathered and obtained a high water content. It is therefore considered safe to use the method of feeding an ongoing burn. The boom is filled up to maximum capacity after 34 minutes according to Equation 14, before it is ignited and fed with more oil. During the DWH response, the burn time was between 10 minutes and 12 hours. In this case the average burn time of two hours, was used [68]. By accounting for one hour to clean up the residue, each team will be able to perform about three burns per day depending on the duration of the burn. Using Equation 19 and the same input values as for the strategy of containing and burning, the residual oil volume will be:

$$V_r = 7.5E9 * \frac{0.023}{1000} - (0.0275 * 150^2) * \frac{2}{1000} * 2 * 60 * 3 * 10 * 5$$

$$V_r = 172\,500 - 22\,276 = 150\,224\; m^3$$

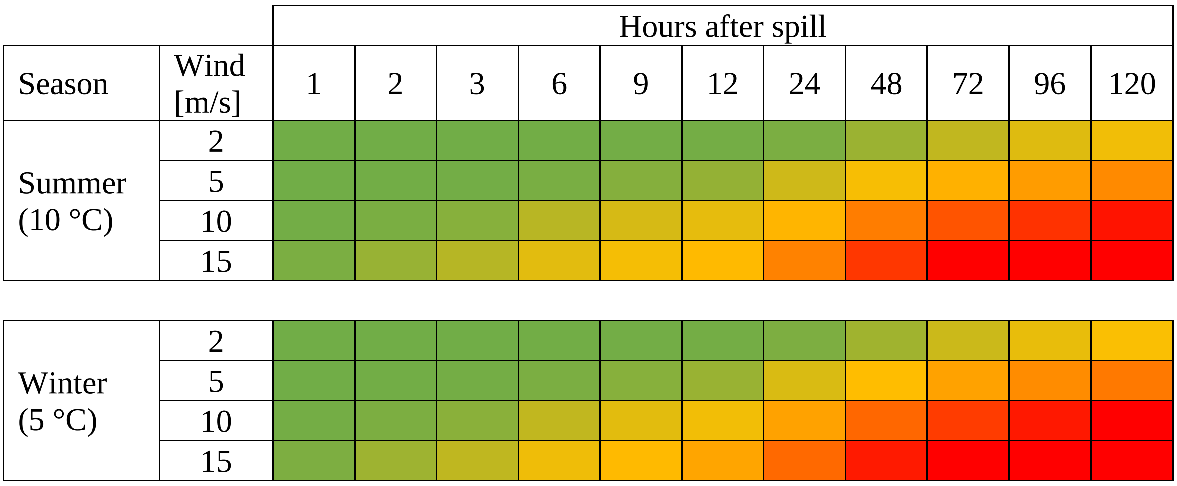
By implementing one *in situ* burning system of feeding an ongoing burn for 10 days, 22 276 m^3 of oil will be recovered and the remaining oil slick volume will be 150 224 m^3, constituting for a 15 % reduction.

4.2.6 Case 3 – Chemical dispersion

As no quantitative model was successfully developed in this thesis, the effectiveness of chemical dispersion is instead qualitatively assessed. Based on the oil's characteristics and weathering time, it can be placed within one of the effectiveness categories presented in Table 4.2. Skrugard oil has an API gravity of 31, which is within the limits of effective dispersion. The solidification temperature of the oil is well below the water temperature and will not be a limiting factor. As for droplet size, it is difficult to say anything without performing any tests.

When it comes to viscosity, the oil is within the effective range up to 12 hours after the spill in wind speeds up to 5 m/s. The oil is effectively dispersed beyond the first 12 hours and up to 48 hours only in wind speeds less than 5 m/s. At wind speeds of 10 m/s or more, the effectiveness is reduced after 6 to 9 hours. Table 4.6 shows the time window for when chemical dispersion is effective and not. Overall, the time window for an effective response using dispersants is very limited. However, as this is a continuous oil spill, fresh crude oil will continue to reach the surface which can still be effectively dispersed.

Table 4.6 Time window for when chemical dispersion is assumed to be an effective response method for spilled Skrugards oil based on viscosity data from the weathering study performed by SINTEF [23]. Green indicates the category where the method is highly effective, yellow indicates the category of somewhat effective, while red indicates the category of ineffective. A colour gradient is used to indicate that there are no clear cut-off values.



		Hours after spill										
Season	Wind [m/s]	1	2	3	6	9	12	24	48	72	96	120
Summer (10 °C)	2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨
	5	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟧	🟧
	10	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟧	🟧	🟥	🟥
	15	🟩	🟩	🟨	🟨	🟨	🟨	🟧	🟥	🟥	🟥	🟥
Winter (5 °C)	2	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨
	5	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟧	🟧	🟧
	10	🟩	🟩	🟩	🟨	🟨	🟨	🟧	🟧	🟥	🟥	🟥
	15	🟩	🟩	🟨	🟨	🟨	🟧	🟧	🟥	🟥	🟥	🟥

4.2.7 Ecosystem impact

An ERA performed by the research institute Akvaplan-Niva (Norway) identifies birds as the most vulnerable group, more exact the guillemot species and Atlantic puffin, which are present in the influence area all year round. Table 4.7 shows that the probability for severe environmental damage is highest from April to June during nesting season. In case of serious damage, the restitution time, the time necessary for the population to regain its population number to 99 % of the size before the spill, is assumed to be more than 10 years. The VEC of highest risk in the influence area at that time is the Atlantic puffin. The largest impact will still be out in the open ocean where pelagic divers dive for food source in the water surface [77].

Table 4.7 Maximum levels of environmental risk for the species with the highest risk in the MIRA analysis performed for each season. The analysis is performed by Akvaplan-Niva in cooperation with Statoil with regards to the PDO for Johan Castberg. The values represent the risk levels as a percentage of Statoil's field-specific acceptance criteria. The numbers in brackets on the first row represent the expected restitution time [80].

Season	VEC	Minor damage (<1 year)	Moderate damage (1-3 years)	Significant damage (3-10 years)	Serious damage (>10 years)
Jan-Mar	Common Guillemot (open sea)	9 %	35 %	5 %	7 %
Apr-Jun	Puffin (coastal)	1 %	4 %	3 %	25 %
Jul-Sep	Puffin (open sea)	9 %	40 %	6 %	7 %
Oct-Dec	Common Guillemot (open sea)	6 %	26 %	4 %	5 %

Mechanical recovery is presumably the response system with the least negative impact on the ecosystem, due to the fact that it recovers and removes the oil entirely. The greatest issue is the time and equipment required. The longer the oil is in the environment, the greater is the risk of organisms getting in contact with the oil slick.

"The solution to pollution is dilution" is an old saying that has often been mistakenly interpreted. However, in the case of an oil spill response, it may be true. *In situ* burning dilutes the combusted oil compounds into the atmosphere and chemical dispersants dilute the oil into the water column. It may still cause some harm, but observations and monitoring have demonstrated that the overall impact is reduced [17, 34, 38, 62].

In the case study, *in situ* burning had an effectiveness between 12 and 15 %. The oil will quickly be removed from the water surface, decreasing the potential for birds and mammals coming in contact with the slick. As long as the burn residue is quickly recovered after a burn, there is no risk that organisms in the ocean will be impacted by the method. Because of the remote location, the smoke plume will not be an issue.

If chemical dispersants can be used, it will also minimise the area of the slick, decreasing the risk of birds and mammals. Because of the depth of the water column, corals and swamps are not considered to be harmed by the dispersed oil. As stated by Gardiner et al., the concentration of oil dispersed into the water column, will be above the toxic concentration around 12 mg/L. However, the high concentration will quickly be reduced by the turbulence and be below toxic levels within 50 minutes [39].

4.3 Discussion

Given the API gravities for the different crude oils in the Barents Sea presented in the NOFO dataset, all oils have APIs above 31 and are according to the classification in Chapter 2.3.2 considered as light crude oils. This is the most toxic type of crude oil with large concentrations of BTEX. It is crucial that the toxic compounds evaporate during the first hours after the spill, before the oil is dispersed into the water column. From the data presented in Figure 2.5, there is no significant difference in the evaporative loss due to temperature changes between the winter and summer season, but must be expected to be lower in Arctic areas compared to more temperate areas.

From DNV GLs response gap analysis and the results presented in Table 2.2, mechanical recovery and chemical dispersion appear to be the best suited response systems for the Arctic environment. The summer season, from June to August, is the period when response systems can be most successfully implemented with an average applicability of 77 %. While in winter, from December to February, there is only a 43 % chance that a response system will be successfully implemented. Still, this is the period when the wind is at its highest and contributes the most to natural dispersion. During spring, when many organisms are in their most vulnerable state, the applicability is below 48 %. It should therefore be considered if the most hazardous activities, such as drilling, can be avoided during this season.

From the quantitative models derived in Chapter 4.1 and the case study in Chapter 4.2, mechanical recovery is the most effective response system when comparing volume of oil removed from the water surface. Mechanical recovery removes 49 995 m^3 after 10 days of cleaning, leaving behind a residual oil volume of 122 505 m^3. This is a reduction of 29 %. Feeding an ongoing burn is the strategy yielding the highest effectiveness out of the two *in situ* burning models. A volume of 22 276 m^3 is removed, leaving behind 150 224 m^3 of oil, accounting for a reduction of 15 %. The less effective strategy of separately containing and burning the oil, removes 20 600 m^3, leaving behind a residual oil volume of 151 900 m^3. This is a reduction of 12 % of the total oil volume. The large difference is mainly due to the swath width, resulting in different ERs. The width must be smaller for *in situ* burning to better control the fire, while for mechanical recovery it depends on the spreading of the oil, speed of the tow boats, and system configuration.

From the comparison with the calculators developed by BSEE and Genwest systems in Chapter 4.1.5, it can be argued that the models developed in this thesis produce credible results. Compared to the results from the Johan Castberg case study, where mechanical recovery was the most effective response system, the results obtained from the models in the comparison indicates that *in situ* burning with feeding of an ongoing burn has the highest effectiveness. The reason is the use of different swath widths. In the comparison, swath widths of 35 m and 46 m are used for mechanical recovery and *in situ* burning, instead of 135 m and 50 m which were used in the case study. The ER in the case of a 135 m swath will be almost 4 times greater than in the case of a 35 m width. This shows again the importance of using an optimal swath width.

To develop the models, several assumptions were made, e.g. the assumption that the ER of the oil is 100 % efficient, that the swath is constant, and that the oil slick thickness is uniform. Most of these assumptions can be argued to be accepted because it is believed that the resulting errors are negligible compared to the overall result. Oil slick thickness plays a major role in the calculations, but due to limited data, an assumed average thickness is also used in this case. Temperature was not included as a factor in the models developed in this thesis, because the small variation between summer and winter in the Arctic had little impact on the oil and responses. However, in areas where the temperature fluctuation is of greater amplitude, the temperature should be included as a factor. Not all oil characteristics are considered in the models, e.g. in the model for mechanical recovery only emulsion percentage is included as the other characteristics are considered when the type of skimmer is selected.

Even though mechanical recovery shows a higher effectiveness than *in situ* burning, it also requires more equipment, more personnel, and results in a larger volume of waste. It is also assumed to be the most expensive method out of the two. It can be argued that the effectiveness of mechanical recovery and *in situ* burning are not comparative based only on the volume of oil recovered. If the cost and equipment requirements are taken into consideration, it is likely that the effectiveness of *in situ* burning would be greater than mechanical recovery.

The input value for the burn duration in the case study was set to 2 hours, but burns have been documented to last up to 12 hours. A longer duration can increase the effectiveness of the strategy where oil is fed into an ongoing burn. However, one must also acknowledge that the opposite case may occur, that the burn lasts for less than 2 hours. A shorter burn results in a larger volume of residue that must be recovered mechanically or manually and will most likely decrease the effectiveness. It is uncertain to which extent *in situ* burning will be successful in the Arctic due to the high emulsion rates. Experiments have proven that oil with high water content can burn, but it is not an established fact.

Mechanical recovery induce little harm to the surrounding environment and the created model indicates that the recovery rate is good. It is the most expensive response method, but one must decide whether the expenses are worth the benefits of the system. *In situ* burning creates a plume of black smoke which for many people are immediately negatively interpreted as more pollution and contamination. The smoke should be monitored, but is not assumed to cause any irreversible effects. Distribution of information on *in situ* burning will increase the awareness of the response method, and can potentially decrease the negative conception of a proven effective method. There is a greater chance that the oil residue will sink after being burned, due to property changes. Since the bottom fauna in the Barents Sea-Lofoten management plan area is of great concern due to the rare deep-water corals, this response should be avoided in certain areas. According to NOFO, *in situ* burning has not been considered a response method because of the narrow weather limitations in the area. Weathering studies indicate that the oils found in the Arctic have high emulsion rates which make ignition difficult. However, one must not forget that the industry is moving into ice infested waters where *in situ* burning is proven to be very effective, and mechanical recovery less effective. *In situ* burning is also considered to be the least costly response method.

A quantitative effectiveness model for chemical dispersion was not successfully developed in this thesis. However, data from the DWH accident indicates that this method is highly effective compared to the other two systems mentioned. It has been estimated that chemical dispersion accounted for the removal of 10.2 % of the spilled volume, about 500,000 bbl of oil, while mechanical recovery accounted for 1.5 to 6.1 % and *in situ* burning accounted for 4.5 to 6.3 %. Based on the qualitative model developed in Chapter 4.1.3, spilled Skrugard oil can be treated with dispersant chemicals up to 24 hours after surfacing, but will only have a high effectiveness in wind speeds less than 2 m/s and only the first 14 hours of the response. From the case study, it appears that the long response time to the field and the properties of the oil highly decrease the window of opportunity. A chemical dispersant system does not appear to be the most effective response for the Barents Sea-Lofoten management area.

Already existing models focus mainly on the logistics and volume of oil that is treated with dispersants, but none account for the actual effectiveness. Dispersants will increase the bioavailability of the oil, which again will increase the biodegradation and quickly reduce the oil concentration to below toxic levels. Chemically dispersed oil is also proven to induce less toxicological effects than physically dispersed oil. Due to the long response time, the most toxic compounds, such as BTEX, will have evaporated before the oil is dispersed. Based on the dose-response data in Chapter 2.2.3 and the fact that the dispersed oil does not stay in the water column longer than 2 to 4 hours, it can be expected that the method will highly decrease the resulting mortality from an oil spill. Still, due to contradicting results, further study should be conducted.

No existing model can quantitatively affiliate the decrease in oil slick volume with the change in impact on the ecosystems at risk. Organisms are affected by oil in various ways, e.g. by ingesting toxic compounds or becoming covered in oil, and response systems combat the oil spill in different ways, e.g. diluting or recovering. Because of this, the existing models have only focused on one type of response or one group of organisms at a time. Hence, the total ecosystem risk can only be described in a qualitative way.

Because the greatest risk is the pelagic divers, the response should focus on decreasing the area of the slick as quickly as possible. If dispersants can be successfully used, this response should be implemented as soon as possible. However, in the open Arctic Ocean, the wind speed is rarely 2 m/s for a longer period and one should expect that this response method will not be successful. Mechanical recovery is then the preferred option, as it removes the oil from the environment entirely. The distance from the field to a waste disposal terminal is long, but tank ships can be used for temporary storage. The Johan Castberg field is far south from the MIZ and very little ice debris is expected in this area. As the oil industry moves further north into the Barents Sea, towards the MIZ, a larger concentration of ice debris is more probable.

5. Limitations

This thesis has, like most others, some limitations. It relies fully on and is limited to existing literature from government reports, scientific papers, published reports, and information on oil spill response systems from various organisations. It is only based on a theoretical approach, which means that it is not tested in real life.

Also, seeing that it only uses secondary data, one cannot be entirely certain that these are reliable or that the information is interpreted as intended by the authors. This will always be a challenge, and it cannot be prevented in any other way than to check the sources carefully. The author’s view on the situation must also be considered when reading the reports. For this thesis governmental reports are assumed to be impartial, whereas non-governmental organisations, such as WWF, may be prejudiced to one side and the petroleum industry to the opposite side.

6. Conclusion

Based on the objectives in Chapter 1.3, two quantitative models and one qualitative model have been derived for the different response systems and their uncertainties have been considered. Further, the vulnerability of Arctic ecosystems has been determined and the impact of the different response systems on these ecosystems have been assessed. Knowledge gaps related to oil spill response in the Arctic have been identified and will be discussed in this chapter.

6.1 My conclusion

As we all know, there is only one earth, and the importance of taking care of it increases in line with the use of its resources. As discussed in this thesis, oil spills present a big threat to today's ecosystems and it can have a major impact on the environment, both within a short distance of the oil spill, but also at a greater distance. It all depends on the response systems, how quickly they can be initiated and how well they work under the given conditions.

The main objective of this thesis was to develop quantitative models to determine the effectiveness of the most commonly used response systems, with focus on deployment in the Arctic. To do so, the main factors affecting the systems had to be identified and the operating environment had to be investigated. By studying the present models, the uncertainties and weaknesses with today's models were also identified and evaluated. When choosing a response method, the focus should not only be directed at the effectiveness, but also on the environmental impact. This thesis therefore identified the most vulnerable areas in the Barents Sea-Lofoten management plan area and assessed the potential impact from the various response systems.

The two quantitative effectiveness models developed are adapted to the Barents Sea-Lofoten management plan area, as they are based on the major influencing factors identified in this area. Among all the identified factors, type of oil, oil slick thickness, response time, wind, and water-in-oil emulsion rate seems to be the determining factors.

Today, mechanical recovery is the available response method best suited for an oil spill response to the fields presently active in the Barents Sea-Lofoten management plan area. It is also the response method inducing the least harm to the environment. Due to the remote location of oil fields in the Barents Sea and the potential presence of ice, *in situ* burning should be considered a potential response method on the NCS. The lack of need for infrastructure, equipment and personnel, and long distance to populations make this an attractive response method. This method increases the risk of impacting the bottom fauna, as burn residue has a higher potential to sink. Hence, the sea bottom should be surveyed and approved for this method. Chemical dispersion is most likely the method with the highest effect in regard to preventing an oil spill from reaching a sensitive area with vulnerable and endangered species. It is also considered to be the cheapest response method and the best way of reducing shoreline contamination. A thought provoking question is whether one should accept the use of possible toxic dispersants, if the total outcome is positive. Still, chemical dispersion does not appear to be a suitable alternative in the Barents Sea-Lofoten management plan area because of the limited response window.

Oil slick thickness is identified as the major source of uncertainty for the existing models and so far, there is no available technology for more precise determination. The environmental factors are difficult to determine more precisely other than to monitor and forecast, while the oil properties can be mapped through weathering studies.

Based on this literature study, Arctic species do not appear to be more vulnerable than those in temperate areas. However, the different species seem to be more dependent on each other, causing the ecosystem as a whole to be more vulnerable and sensitive to changes. There have been identified four ecosystems in the Barents Sea-Lofoten management plan area, comprising eight areas of higher vulnerability, but as a general rule an overall precaution should always be taken.

6.2 Future research

As seen in this thesis, future research is highly needed to better determine the effects of the response systems. The effectiveness of the systems can be estimated, but various models seem to conclude differently. The environmental impacts due to the responses and the Arctic environment itself are neither fully understood.

Further research must focus on finding better methods to determine the real-time oil slick thickness, which in this thesis is found to be the largest uncertainty. A more exact determination of the thickness will be of great importance in the development of more accurate quantitative models and to improve the efficiency of the response.

There are still many unanswered questions regarding chemical dispersants and on this subject further research should focus on understanding the processes involved when applying the dispersant. In order to develop an effectiveness model, more information and understanding is needed about dispersant penetration rate into the oil slick, the droplet formation rate, and the biodegradation rate. The long-term effects of dispersants, their toxicity, persistence, and bioaccumulation in the ecosystem should also be further investigated.

Most models, including the models developed in this thesis, use the volume of oil that is removed from the water surface to determine the effectiveness of the system. Future models should also consider other perspectives, such as estimated cost, waste, personnel and equipment requirements.

7. References

[1] K. J. Bird, R. R. Charpentier, D. L. Gautier, D. W. Houseknecht, T. R. Klett, J. K. Pitman, T. E. Moore, C. J. Schenk, M. E. Tennyson, and C. J. Wandrey, "*Circum-Arctic resource appraisal; estimates of undiscovered oil and gas north of the Arctic Circle*", Fact Sheet 2008-3049, U.S. Geological Survey, 2008.

[2] Norwegian Ministry of Climate and Environment, Meld. St. 20 (2014–2015), *"*Update of the integrated management plan for the Barents Sea–Lofoten area including an update of the delimitation of the marginal ice zone*"*, 2015.

[3] Norwegian Petroleum Directorate, *Factpages*, Available: www.factpages.npd.no, Accessed on: 09.02.18.

[4] Encyclopædia Britannica, *Ecosystem - Definition, Components, & Structure* [Online dictionary], Available: https://www.britannica.com/science/ecosystem, Accessed on: 20.04.18.

[5] Norwegian Ministry of Climate and Environment, Meld. St. 8 (2005-2006), *"*Helhetlig forvaltning av det marine miljø i Barentshavet og havområdene utenfor Lofoten (forvaltningsplan)*"*, 2006.

[6] Faglig forum for norske havområder, "Særlig verdifulle og sårbare områder i Barentshavet", Miljøstatus, 2017.

[7] DNV GL, "Development of Methodology for Calculations of Environmental Risk for the Marginal Ice Zone - A joint project between Akvaplan-Niva and DNV GL", 2014.

[8] S. Henriksen and O. Hilmo, "The Norwegian Red List 2015", Artsdatabanken, 2015.

[9] L. Buhl-Mortensen, H. Hodnesdal, and T. Thorsnes, *The Norwegian Sea Floor - New Knowledge from MAREANO for Ecosystem-Based Management*, Skipnes press, 2015.

[10] Norwegian Ministry of Climate and Environment, Meld. St. 10 (2010-2011), *"*First update of the Integrated Management Plan for the Marine Environment of the Barents Sea-Lofoten Area*"*, 2011.

[11] O. W. Brude and M. Rusten, "Species vulnerability and their use in oil spill risk assessments", in *Assessing vulnerability of flora and fauna in polar areas: symposium proceedings*, D. Vongraven, Norwegian Polar Institute, 2015, pp. 63-67.

[12] Oljeindustriens landsforening, "Metode for miljørettet risikoanalyse (MIRA) revisjon 2007", Norsk olje og gass, report nr. 2007-0063, 2007.

[13] A. C. Bejarano, W. W. Gardiner, M. G. Barron, and J. Q. Word, "Relative sensitivity of Arctic species to physically and chemically dispersed oil determined from three hydrocarbon measures of aquatic toxicity", in *Marine Pollution Bulletin*, vol. 122, 2017, pp. 316-322, https://doi.org/10.1016/j.marpolbul.2017.06.064.

[14] L. Camus and M. G. D. Smit, "Environmental effects of Arctic oil spills and spill response technologies, introduction to a 5 year joint industry effort", in *Marine Environmental Research*, 2018, https://doi.org/10.1016/j.marenvres.2017.12.008.

[15] V. Broje, "Toxicity of Oil to Arctic Organisms and Natural Oil Biodegradation", in "*Arctic Potential: Realising the Promise of U.S. Arctic Oil and Gas Resources*", N. P. C. (NPC), report nr. 8-8, 2014.

[16] H. P. Huntington, "Arctic Oil and Gas 2007", Arctic Monitoring and Assessment Programme (AMAP), 2007, 978-82-7971-048-6.

[17] J. N. Boyd, J. H. Kucklick, D. K. Scholz, A. H. Walker, R. G. Pond, and A. Bostrom, "Effects of Oil and Chemically Dispersed Oil in the Environment", American Petroleum Insitute, 2001.

[18] D. Scholz, S. R. Warren, A. H. Walker, and J. Michel, "In situ burning - the fate of burned oil", American Petroleum Institute, API Publishing Services, 2004.

[19] A. Ingvarsdottir, "BioSea II JIP: Effects of Goliat oil on Atlantic halibut (Hippoglossus hippoglossus) metamorphosis larvae", [Unpublished work], 2009.

[20] O. W. Brude, K. R. Sørheim, I. Singsaas, R. L. Daae, Ø. Johansen, and A. Bjørgesæter, "Beredskapsanalyse for produksjonsboring på Goliat", ENI Norge AS, 2011.

[21] M. Fingas, "Chapter 3 - Introduction to Oil Chemistry and Properties" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 51-59, https://doi.org/10.1016/B978-1-85617-943-0.10003-6.

[22] T. Coolbaugh, W. Darbonne, E. DeMicco, P. Foley, R. Freeman, A. George-Ares, R. Hayward, B. Higgins, J. Hoban, D. Kagan, W. Konkel, A. Leonard, L. Morgan, T. Nedwed, A. Nicoll, D. Palandro, R. Pond, W. Putman, J. Sheffer, A. Steen, D. Sweeten, R. Williams, R. Woods, J. Young, and M. Ziccardi, "Oil Spill Response Field Manual", ExxonMobil Research and Engineering Company, 2014.

[23] J. H. C. Øksenvåg, "Skrugard crude oil - weathering studies", SINTEF Materials and Chemistry, NOFO, report nr. 801949, 2012, 978-82-14-05260-2.

[24] J. R. Payne, G. D. McNabb Jr, and J. R. Clayton Jr, "Oil-weathering behavior in Arctic environments", in *Polar Research*, vol. 10, no. 2, 1991, pp. 631-662, 1991/01/12, 10.3402/polar.v10i2.6774.

[25] M. Fingas, "Chapter 8 - Introduction to Spill Modeling" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 187-200, https://doi.org/10.1016/B978-1-85617-943-0.10008-5.

[26] G. Challenger and G. Mauseth, "Chapter 32 - Seafood Safety and Oil Spills A2 - Fingas, Mervin" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 1083-1100, https://doi.org/10.1016/B978-1-85617-943-0.10032-2.

[27] M. Fingas, "Chapter 15 - Oil Spill Dispersants: A Technical Summary" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 435-582, https://doi.org/10.1016/B978-1-85617-943-0.10015-2.

[28] M. Fingas, "Chapter 23 - An Overview of In-Situ Burning" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 737-903, https://doi.org/10.1016/B978-1-85617-943-0.10023-1.

[29] International Tanker Owners Pollution Federation (ITOPF), "TIP 02: Fate of marine oil spills", in "*Technical Information Papers*", 2014.

[30] A. Melbye, L.-G. Faksness, J. Fritt-Rasmussen, T. Bakke, and O. Titov, "Transport and Fate of Oil in the Arctic", Section 3, in *Environmental Impacts of Arctic Oil Spills and Arctic Spill Response Technologies*, J. Q. Word, Arctic Oil Spill Response Technology Joint Industry Programme, 2014, pp. 65-79.

[31] Forvitringsdata [Excel-format], NOFO, www.nofo.no/planverk/datasett/oljetyper-og-egenskaper/forvitringsdata-i-excelformat/.

[32] M. Fingas, "Chapter 12 - Physical Spill Countermeasures" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 303-337, https://doi.org/10.1016/B978-1-85617-943-0.10012-7.

[33] P. Li, Q. Cai, W. Lin, B. Chen, and B. Zhang, "Offshore oil spill response practices and emerging challenges", in *Marine Pollution Bulletin*, vol. 110, no. 1, 2016, pp. 6-27, https://doi.org/10.1016/j.marpol.2014.06.003.

[34] National Research Council, *An Ecosystem Services Approach to Assessing the Impacts of the Deepwater Horizon Oil Spill in the Gulf of Mexico*, Washington DC, The National Academies Press, 2013, p. 246.

[35] D. Dave and A. E. Ghaly, "Remediation Technologies for Marine Oil Spills: A Critical Review and Comparative Analysis ", in *American Journal of Environmental*

Sciences, vol. 7, no. 5, 2011, pp. 423-440, https://doi.org/10.3844/ajessp.2011.423.440.

[36] Nuka Research and Planning Group LLC, "Oil Spill Response Challenges in Arctic Waters", WWF International Arctic Programme, 2007, 978-2-88085-283-2.

[37] J. K. Økland, "*Recovery of Oil Spills in Marine Arctic Regions*", NTNU, 2000.

[38] M. Fingas, "Chapter 10 - In-situ Burning: An Update" in *Oil Spill Science and Technology, 2nd Edition*, Gulf Publishing Company, 2017, pp. 483-576.

[39] NOFO [Personal communication], 08.03.18.

[40] P. J. Brandvik, P. S. Daling, L. G. Faksness, J. Fritt-Rasmussen, R. L. Daae, and F. Leirvik, "Experimental Oil Release in Broken Ice - A Large-Scale Field Verification of Results From Laboratory Studies of Oil Weathering and Ignitability of Weathered Oil Spills", in "*Oil in Ice - JIP*", SINTEF, report nr. 26, 2010.

[41] D. Dickins, P. J. Brandvik, J. Bradford, L.-G. Faksness, L. Liberty, and R. Daniloff, "2006 Svalbard Experimental Spill to Study Spill Detection and Oil Behavior in Ice", 2006.

[42] T. Coolbaugh and A. McElroy, "Dispersant Efficacy and Effectiveness", 2011.

[43] W. W. Gardiner, J. Q. Word, J. D. Word, R. A. Perkins, K. M. McFarlin, B. W. Hester, L. S. Word, and C. M. Ray, "The acute toxicity of chemically and physically dispersed crude oil to key arctic species under arctic conditions during the open water season", in *Environmental Toxicology and Chemistry*, vol. 32, no. 10, 2013, pp. 2284-2300, https://doi.org/10.1002/etc.2307.

[44] H. P. Huntington, R. Daniel, S. Ganey, M. Heiman, E. Huffines, E. Humphries, L. Nipper, and M. Prior-Parks, "Arctic Standards: Recommendations on Oil Spill Prevention, Response, and Safety in the U.S. Arctic Ocean", Pew Charitable Trusts, 2013.

[45] Nuka Research and Planning Group LLC, "Estimating an Oil Spill Response Gap for the U.S. Arctic Ocean (Revised)", BSEE, 2016.

[46] International Tanker Owners Pollution Federation (ITOPF), "TIP 04: Use of dispersants to treat oil spills", in "*Technical Information Papers*", 2014.

[47] EPPR, "Field Guide for Oil Spill Response in Arctic Waters", Arctic Council Secretariat, ed. 2, 2017.

[48] SINTEF, *OSCAR - Oil Spill Contingency and Response* [Webpage], Available: https://www.sintef.no/en/software/oscar/, Accessed on: 20.05.18.

[49] Petroleum Safety Authority, *Facts About the Far North*, Available: http://www.ptil.no/facts-the-far-north/category1143.html, Accessed on: 25.01.18.

[50] DNV GL, "Oil spill response in the Barents Sea South East - Status document", Barents Sea Exploration Collaboration (BaSEC), Norsk olje og gass, report nr. 2015-0997, Rev. 0, 2015.

[51] NOFO, *Planverk*, Available: www.nofo.no/planverk, Accessed on: 24.04.18.

[52] Norwegian Oil and Gas Association, "Veiledning for miljørettede beredskapsanalyser", 2013.

[53] M. Fingas, "Chapter 1 - Introduction" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 3-5, https://doi.org/10.1016/B978-1-85617-943-0.10001-2.

[54] D. P. Prendergast and P. M. Gschwend, "Assessing the performance and cost of oil spill remediation technologies", in *Journal Of Cleaner Production*, vol. 78, 2014, pp. 233-242, http://dx.doi.org/10.1016/j.jclepro.2014.04.054.

[55] I. C. White and F. C. Molloy, "Factors that determine the cost of oil spills", presented at the International Oil Spill Conference, Vancouver, Canada, 6-11 April, 2003.

[56] D. S. Etkin, "Comparative methodologies for estimating on-water response costs for marine oil spills", in *International Oil Spill Conference Proceedings: March 2001*, vol. 2001, no. 2, 2001, pp. 1281-1289, https://doi.org/10.7901/2169-3358-2001-2-1281.

[57] J. Montewka, M. Weckström, and P. Kujala, "A probabilistic model estimating oil spill clean-up costs – A case study for the Gulf of Finland", in *Marine Pollution Bulletin*, vol. 76, 2013, pp. 61-71, http://dx.doi.org/10.1016/j.marpolbul.2013.09.031.

[58] M. Fingas, "Chapter 13 - Weather Effects on Oil Spill Countermeasures" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 339-426, https://doi.org/10.1016/B978-1-85617-943-0.10013-9.

[59] G. Coelho, J. Clark, J. Staves, L. Essex, P. Daling, C. Beegle-Krause, F. Merlin, A. Zhilin, and J. Q. Word, "Net Environmental Benefit Analyses for Oil Spill Response Options", Section 9, in *Environmental Impacts of Arctic Oil Spills and Arctic Spill Response Technologies*, J. Q. Word, Arctic Oil Spill Response Technology Joint Industry Programme, 2014, pp. 184-204.

[60] IPIECA, IOGP, and API, "Guidelines on implementing spill impact mitigation assessment (SIMA)", 2017.

[61] *Residues from In Situ Burning of Oil on Water* [Online article], Available: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/resources/residues-in-situ-burning-oil-water.html, Accessed on: 22.01.18.

[62] Centers for Disease Control and Prevention, "*Oil Spill Dispersant (COREXIT ®EC9500A and EC9527A Information for Health Professionals"*, 2010.

[63] L. J. Hamdan and P. A. Fulmer, "Effects of COREXIT® EC9500A on bacteria from a beach oiled by the Deepwater Horizon spill", in *Aquatic Microbial Ecology*, vol. 63, no. 2, 2011, pp. 101-109.

[64] C. M. Couillard, K. Lee, B. Légaré, and T. L. King, "Effect of dispersant on the composition of the water-accommodated fraction of crude oil and its toxicity to larval marine fish", in *Environmental Toxicology and Chemistry*, vol. 24, no. 6, 2005, pp. 1496-1504, https://doi.org/10.1897/04-267R.1.

[65] BSEE and Genwest Systems, "Estimated Burn System Potential (EBSP) Calculator User Manual", 2016.

[66] BSEE and Genwest Systems, "Estimated Recovery System Potential (ERSP) Calculator User Manual", 2015.

[67] A. Lewis, "Current status of the BAOAC (Bonn Agreement Oil Appearance Code)", 2007.

[68] A. A. Allen, D. Jaeger, N. J. Mabile, and D. Costanzo, "The Use of Controlled Burning during the Gulf of Mexico Deepwater Horizon MC-252 Oil Spill Response", in *International Oil Spill Conference Proceedings*, no. 1, 2011, https://doi.org/10.7901/2169-3358-2011-1-194.

[69] BSEE and Genwest Systems, "Estimated Dispersant System Potential (EDSP) Calculator Manual", 2016.

[70] Genwest Systems, "Response Option Calculator (ROC) Technical Document", 2011.

[71] IPIECA-IOGP, "At-sea monitoring of surface dispersant effectiveness", in "*Oil spill response joint industry project*", 2015.

[72] A. A. Allen, J. A. Galt, D. H. Dale, and J. A. Murphy, "EDRC project final report", Genwest Systems, Inc., , 2012.

[73] M. Fingas and C. E. Brown, "Chapter 6 - Oil Spill Remote Sensing: A Review" in *Oil Spill Science and Technology*, Gulf Professional Publishing, 2011, pp. 111-169, https://doi.org/10.1016/B978-1-85617-943-0.10006-1.

[74] A. A. Allen, D. H. Dale, J. A. Galt, and J. A. Murphy, "EDRC Project Final Report", Genwest Systems and Spiltec, BSEE, 2012.

[75] I. H. Elhajj, D. Asmar, M. Saleh, and G. Oueidat, "Development of Oil Slick Thickness Sensors", Bureau of Safety and Environmental Enforcement, 2018.

[76] ISCO, "Sensors For Oil Slick Detection and Thickness Measurement", in *ISCO Newsletter*, no. 626, 2018.

[77] Statoil, "PL532 Johan Castberg, PUD del II - Konsekvensutredning", 2017.

[78] L. Prendergast and M. Jeans, "B727 Mobilisation and Logistics Plan", Oil Spill Response Limited, 2017.

[79] NOFO, *Common Operational Picture Oil Spill Response (COP OSR)* [Online map service], Available: https://cop.nofo.no, Accessed on: 27.04.18.

[80] C. Stephansen, T. Sørnes, and G. M. Skeie, "Miljørisikoanalyse. Johan Castberg - produksjonsboring og drift", Akvaplan-niva AS, Statoil, report nr. 8610.01, 2017.

Appendixes

Appendix 1: Dose-response data from research study on Atlantic Halibut [19].

Dose (Concentration)	Response (Mortality)	
(Nominal) Oil	Accumulated 28d mortality	
(mg oil/L)	(%)	
0	34,9	Control with “background” mortality
0,015	42,8	
0,06	41,2	
0,25	45,6	NOEC (No Observed Effect Concentration)
0,75	82,3	LOEC (Lowest Observable Effect Concentration)

Appendix 2: Data retrieved from NOFO’s oil weathering database [31].

Temperature [°C]	Wind [m/s]	Time [hrs]	Water content [%]	Viscosity [cP]	Evaporated [%]	Surface oil [%]	Dispersed [%]	Solidification temperature [°C]	API
5	2	1	3.0	45	2.0	97.0	0.0	-17.6	31
5	2	2	6.0	54	3.0	96.0	0.0	-16.8	31
5	2	3	9.0	62	4.0	95.0	0.0	-16.2	31
5	2	6	16.0	90	5.0	94.0	0.0	-15.1	31
5	2	9	24.0	125	6.0	93.0	0.0	-14.3	31
5	2	12	30.0	169	7.0	92.0	0.0	-13.7	31
5	2	24	49.0	466	9.0	90.0	0.0	-12.0	31
5	2	48	68.0	1700	12.0	87.0	0.0	-10.0	31
5	2	72	75.0	3190	13.0	86.0	0.0	-8.7	31
5	2	96	77.0	4230	14.0	85.0	0.0	-7.8	31
5	2	120	78.0	4840	15.0	84.0	0.0	-7.1	31
5	5	1	11.0	64	3.0	96.0	0.0	-16.9	31
5	5	2	21.0	99	4.0	95.0	0.0	-15.9	31
5	5	3	30.0	146	5.0	94.0	0.0	-15.2	31
5	5	6	49.0	394	7.0	91.0	0.0	-13.8	31
5	5	9	60.0	839	8.0	89.0	1.0	-12.6	31
5	5	12	68.0	1440	9.0	88.0	1.0	-11.7	31
5	5	24	78.0	3700	12.0	84.0	2.0	-9.5	31
5	5	48	79.0	5090	15.0	80.0	4.0	-7.2	31
5	5	72	79.0	5800	17.0	76.0	6.0	-5.8	31

5	5	96	79.0	6380	18.0	74.0	7.0	-4.7	31
5	5	120	79.0	6870	19.0	71.0	8.0	-3.9	31
5	10	1	33.0	156	4.0	93.0	1.0	-15.7	31
5	10	2	52.0	439	6.0	90.0	3.0	-14.5	31
5	10	3	63.0	928	7.0	87.0	5.0	-13.5	31
5	10	6	76.0	2840	10.0	79.0	10.0	-11.1	31
5	10	9	79.0	4020	12.0	73.0	14.0	-9.6	31
5	10	12	79.0	4580	13.0	68.0	17.0	-8.5	31
5	10	24	79.0	5790	17.0	54.0	29.0	-6.0	31
5	10	48	79.0	7340	20.0	36.0	44.0	-3.4	31
5	10	72	79.0	8450	22.0	25.0	54.0	-1.8	31
5	10	96	79.0	9380	23.0	18.0	61.0	-0.7	31
5	10	120	79.0	10200	24.0	13.0	65.0	0.3	31
5	15	1	54.0	466	6.0	86.0	7.0	-14.8	31
5	15	2	71.0	1610	8.0	77.0	14.0	-13.2	31
5	15	3	77.0	2790	9.0	69.0	21.0	-11.8	31
5	15	6	79.0	4470	13.0	50.0	37.0	-8.9	31
5	15	9	79.0	5170	15.0	37.0	48.0	-7.3	31
5	15	12	79.0	5720	16.0	28.0	56.0	-6.2	31
5	15	24	79.0	7290	19.0	10.0	73.0	-3.6	31
5	15	48	79.0	9340	23.0	1.0	81.0	-0.8	31
5	15	72	79.0	10900	25.0	0.0	82.0	0.9	31
5	15	96	79.0	12200	26.0	0.0	82.0	2.1	31
5	15	120	79.0	13400	28.0	0.0	82.0	3.2	31
10	2	1	3.0	38	2.0	97.0	0.0	-17.4	31
10	2	2	6.0	45	3.0	96.0	0.0	-16.5	31
10	2	3	9.0	52	4.0	95.0	0.0	-15.9	31
10	2	6	16.0	76	6.0	93.0	0.0	-14.7	31
10	2	9	24.0	107	7.0	92.0	0.0	-13.8	31
10	2	12	30.0	146	8.0	91.0	0.0	-13.0	31
10	2	24	49.0	410	10.0	89.0	0.0	-11.0	31
10	2	48	68.0	1510	13.0	86.0	0.0	-8.8	31
10	2	72	75.0	2860	15.0	84.0	0.0	-7.4	31
10	2	96	78.0	3880	16.0	83.0	0.0	-6.4	31
10	2	120	79.0	4530	17.0	82.0	0.0	-5.6	31
10	5	1	11.0	54	3.0	96.0	0.0	-16.6	31
10	5	2	21.0	84	5.0	94.0	0.0	-15.6	31
10	5	3	30.0	124	5.0	93.0	0.0	-14.8	31
10	5	6	49.0	341	8.0	90.0	1.0	-13.1	31
10	5	9	60.0	735	9.0	88.0	1.0	-11.7	31
10	5	12	68.0	1270	11.0	87.0	1.0	-10.7	31
10	5	24	78.0	3300	14.0	82.0	3.0	-8.2	31
10	5	48	80.0	4730	17.0	78.0	4.0	-5.7	31
10	5	72	80.0	5400	19.0	74.0	6.0	-4.2	31
10	5	96	80.0	5940	20.0	71.0	7.0	-3.1	31
10	5	120	80.0	6410	21.0	69.0	9.0	-2.2	31

10	10	1	33.0	133	5.0	93.0	1.0	-15.4	31
10	10	2	52.0	376	7.0	89.0	3.0	-13.9	31
10	10	3	63.0	805	8.0	85.0	5.0	-12.8	31
10	10	6	76.0	2520	12.0	77.0	11.0	-10.0	31
10	10	9	79.0	3580	14.0	71.0	15.0	-8.3	31
10	10	12	79.0	4140	15.0	66.0	18.0	-7.1	31
10	10	24	80.0	5310	18.0	51.0	30.0	-4.4	31
10	10	48	80.0	6750	22.0	34.0	45.0	-1.6	31
10	10	72	80.0	7820	24.0	23.0	55.0	0.1	31
10	10	96	80.0	8720	25.0	16.0	61.0	1.4	31
10	10	120	80.0	9520	27.0	11.0	65.0	2.4	31
10	15	1	54.0	398	6.0	85.0	8.0	-14.3	31
10	15	2	71.0	1400	9.0	75.0	15.0	-12.4	31
10	15	3	77.0	2460	11.0	67.0	22.0	-10.7	31
10	15	6	79.0	4000	15.0	47.0	38.0	-7.6	31
10	15	9	80.0	4670	17.0	34.0	49.0	-5.9	31
10	15	12	80.0	5180	18.0	25.0	58.0	-4.7	31
10	15	24	80.0	6630	22.0	8.0	73.0	-1.8	31
10	15	48	80.0	8590	25.0	1.0	80.0	1.2	31
10	15	72	80.0	10100	28.0	0.0	81.0	3.1	31
10	15	96	80.0	11500	29.0	0.0	81.0	4.7	31
10	15	120	80.0	12900	31.0	0.0	81.0	6.0	31

Appendix 3: Data retrieved from Allen et al. on oil slick thickness [74].

*Oil slick thickness has been converted from inch to mm using a conversion rate of 25.4.

Oil type	Spill volume [bbl]	Temperature [°C]	Wind speed [kts]	Day	Thickness* [mm]
LLS	500000	0	0	1	3.28
LLS	500000	0	5	1	2.95
LLS	500000	0	10	1	12.34
LLS	500000	0	15	1	16.08
LLS	500000	10	0	1	2.39
LLS	500000	10	5	1	2.36
LLS	500000	10	10	1	10.64
LLS	500000	10	15	1	13.69
LLS	500000	15	0	1	2.03
LLS	500000	15	5	1	2.08
LLS	500000	15	10	1	9.55
LLS	500000	15	15	1	12.34
LLS	500000	0	0	2	1.96
LLS	500000	0	5	2	2.29
LLS	500000	0	10	2	12.41
LLS	500000	0	15	2	10.86
LLS	500000	10	0	2	1.51

LLS	500000	10	5	2	1.86
LLS	500000	10	10	2	10.25
LLS	500000	10	15	2	8.66
LLS	500000	15	0	2	1.31
LLS	500000	15	5	2	1.65
LLS	500000	15	10	2	9.22
LLS	500000	15	15	2	7.74
LLS	500000	0	0	3	1.39
LLS	500000	0	5	3	1.91
LLS	500000	0	10	3	9.70
LLS	500000	0	15	3	5.77
LLS	500000	10	0	3	1.10
LLS	500000	10	5	3	1.56
LLS	500000	10	10	3	7.81
LLS	500000	10	15	3	4.67
LLS	500000	15	0	3	0.97
LLS	500000	15	5	3	1.40
LLS	500000	15	10	3	7.00
LLS	500000	15	15	3	4.20
ANS	500000	0	0	1	4.70
ANS	500000	0	5	1	3.66
ANS	500000	0	10	1	14.83
ANS	500000	0	15	1	19.46
ANS	500000	10	0	1	3.43
ANS	500000	10	5	1	3.23
ANS	500000	10	10	1	14.15
ANS	500000	10	15	1	18.01
ANS	500000	15	0	1	2.95
ANS	500000	15	5	1	2.90
ANS	500000	15	10	1	12.95
ANS	500000	15	15	1	16.56
ANS	500000	0	0	2	2.58
ANS	500000	0	5	2	2.88
ANS	500000	0	10	2	15.35
ANS	500000	0	15	2	9.79
ANS	500000	10	0	2	2.07
ANS	500000	10	5	2	2.45
ANS	500000	10	10	2	13.37
ANS	500000	10	15	2	11.30
ANS	500000	15	0	2	1.82
ANS	500000	15	5	2	2.21
ANS	500000	15	10	2	12.12
ANS	500000	15	15	2	10.14
ANS	500000	0	0	3	1.80
ANS	500000	0	5	3	2.39
ANS	500000	0	10	3	8.69

ANS	500000	0	15	3	5.09
ANS	500000	10	0	3	1.47
ANS	500000	10	5	3	2.03
ANS	500000	10	10	3	10.10
ANS	500000	10	15	3	6.02
ANS	500000	15	0	3	1.31
ANS	500000	15	5	3	1.85
ANS	500000	15	10	3	9.13
ANS	500000	15	15	3	5.48
IFO 300	500000	0	0	1	54.69
IFO 300	500000	0	5	1	26.92
IFO 300	500000	0	10	1	47.02
IFO 300	500000	0	15	1	27.94
IFO 300	500000	10	0	1	44.20
IFO 300	500000	10	5	1	22.35
IFO 300	500000	10	10	1	39.62
IFO 300	500000	10	15	1	23.62
IFO 300	500000	15	0	1	39.88
IFO 300	500000	15	5	1	20.42
IFO 300	500000	15	10	1	36.32
IFO 300	500000	15	15	1	21.74
IFO 300	500000	0	0	2	15.13
IFO 300	500000	0	5	2	6.74
IFO 300	500000	0	10	2	11.27
IFO 300	500000	0	15	2	6.54
IFO 300	500000	10	0	2	13.03
IFO 300	500000	10	5	2	5.87
IFO 300	500000	10	10	2	9.84
IFO 300	500000	10	15	2	5.70
IFO 300	500000	15	0	2	12.10
IFO 300	500000	15	5	2	5.48
IFO 300	500000	15	10	2	9.19
IFO 300	500000	15	15	2	5.32
IFO 300	500000	0	0	3	6.91
IFO 300	500000	0	5	3	3.00
IFO 300	500000	0	10	3	4.96
IFO 300	500000	0	15	3	2.86
IFO 300	500000	10	0	3	6.13
IFO 300	500000	10	5	3	2.67
IFO 300	500000	10	10	3	4.41
IFO 300	500000	10	15	3	2.48
IFO 300	500000	15	0	3	5.76
IFO 300	500000	15	5	3	2.52
IFO 300	500000	15	10	3	4.16
IFO 300	500000	15	15	3	2.38