



FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study programme/specialisation: Master of Science in Environmental Engineering	Spring semester, 2019 Confidential
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Title of master's thesis: A modelling study of environmental fate and effects of oil leakage from abandoned wells	
Credits: 30 ECTS	
Keywords: Modelling, abandoned wells, oil leakage, chronic exposure and effects, environmental impact factor (EIF), predicted no effect concentration (PNEC), predicted environmental concentration (PEC).	Number of pages: 103 + supplemental material/other: 0 Stavanger, 15th June 2019

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Abstract

Potential environmental consequences of oil leakages are taken into consideration in the ongoing development of plug and abandonment (P&A) activities on the Norwegian Continental Shelf (NCS). The P&A on the NCS has been required to reach a “zero leakage” target, while environmental regulations and risk monitoring for permanent abandonment are still needed. Thus, a modelling study of fate and effects of oil leakage from abandoned wells is the topic of this thesis. The research covers an investigation into applicable models and scenario modelling of a theoretical oil leak case study on the NCS. Lessons from natural oil seeps are utilized to understand potential exposure and effects of the oil leakages. In order to estimate the chronic biological exposure and effects from continuous low-rate oil leakages, the modelling is executed via a software developed by SINTEF. An Environmental Impact Factor (EIF) tool is used to compute impacted areas and risks of different oil droplets. The results show that the smaller the droplets are, the greater the impact they have on the environment. EIFs or risks develop in time and become more stable over long periods, meanwhile impacted areas with risk > 5% become denser in a certain location of a few hundred meters from the release site. Chronic exposure and effects on organisms potentially occur with a steady state effect over a long period. Some unacceptable risks, which are exceeding the conventional accepted level of 5%, appear surrounding the release site, indicating a need of mitigation measures. Under variation of currents and winds, dilution, dispersion, evaporation, oxidation and biodegradation are parts of the influence processes on fate and effects of the oil leakage. Toxic hydrocarbons including polycyclic aromatic hydrocarbon, naphthalene 1, C4 benzene and C7 to C9 saturates should be of concern regarding hydrocarbon contributions to risks.

Acknowledgements

I would like to express my gratitude and appreciation to my supervisors: Daniela Maria Pampanin at the University of Stavanger, Hans Petter Lohne from the Norwegian Research Centre and Tor Nordam from SINTEF Ocean. I am sincerely grateful for all your kindness, enthusiastic support and advice throughout the course of my studies.

Many thanks to Øystein Arild for providing me with the opportunity to work on this thesis and I appreciate your suggestions and encouraging questions during our meetings.

I would also like to thank Mahmoud Khalifeh for the useful input and experience on the plug and abandonment activities, as well as Emily Lyng for your kind guidance and valuable literatures on the establishing of chronic effect concentration values.

Special thanks to SINTEF Ocean for granting me access to your software and database.

I am also thankful to the IT department at the University of Stavanger for allowing me to borrow necessary equipment and for your quick responses to my technical issues.

Last but not least, I would like to thank my parents, my family and friends for the love and support that have continued to motivate me in pursuing my work.

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Abbreviations

AF	Assessment Factor
ACR	Acute to Chronic Ratio
API	American Petroleum Institute
BCF	Bioconcentration Factor
BTEX	Benzenes, Toluenes, Ethylbenzenes, Xylenes
DNV GL	Det Norske Veritas and Germanischer Lloyd
DREAM	Dose related Risk and Effect Assessment Model
EC ₅₀	Effect Concentration at which 50% of the tested effect is reached
ERA	Environmental Risk Assessment
EPA	Environmental Protection Agency
EC-TGD	European Commission – Technical Guidance Document
EIF	Environmental Impact Factor
HC ₅	Hazardous Concentration Thresholds for 5% of species
IRIS	International Research Institute of Stavanger
ITOPF	The International Tanker Owners Pollution Federation Limited
K _{ow}	Octanol/Water partition coefficient
LC ₅₀	Lethal Concentration at which 50% of the tested individuals die
NCS	Norwegian Continental Shelf
NOEC	No Observed Effect Concentration
NORSOK	Norsk Søkkel Konkurransesepisjon
OSCAR	Oil Spill Contingency and Response
OSPAR	Oslo-Paris Commission
PAH	Polycyclic Aromatic Hydrocarbons
P&A	Plug and Abandonment
PEC	Predicted Environmental Concentration
PNEC	Predicted No Effect Concentration
OECD	Organization for Economic Cooperation and Development
QSAR	Quantitative Structure Activity Relationship
SSD	Species Sensitivity Distribution
TLM	Target Lipid Model
UIS	University of Stavanger

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Introduction

In order to give an overview of main points of the thesis, the introduction in chapter 1 conveys a background, scope and schematic outlines of:

- What the research is interested in;
- Why the thesis topic is chosen;
- How the research ideas will be developed to deal with the research aims and objectives.

1. Background, scope and outline of the thesis

1.1 Thesis topic

To a certain extent, abandoned wells are expected to interact with the marine environment which includes the seafloor, the water column and the sea surface (DNVGL, 2016).

Environmental hazards can result from unplugged or poorly plugged abandoned wells, which provide potential leakage pathways for oil fluids to migrate at low flow rate between formations and potentially seep into drinking water aquifers (Global CCS Institute, 2018).

The oil when enters the ocean from the seabed with small release amount over long periods is relatively unweathered in comparison with other sources that reaches the bottom (National Research Council, 2003b). It can possibly become a chronic exposure of marine organisms to oil and its chemical components. Natural oil seeps that have been leaking continuously at very low rate for thousands of years in many parts of the ocean can be referred to understand the effects of oil on the marine ecosystem (ibid.).

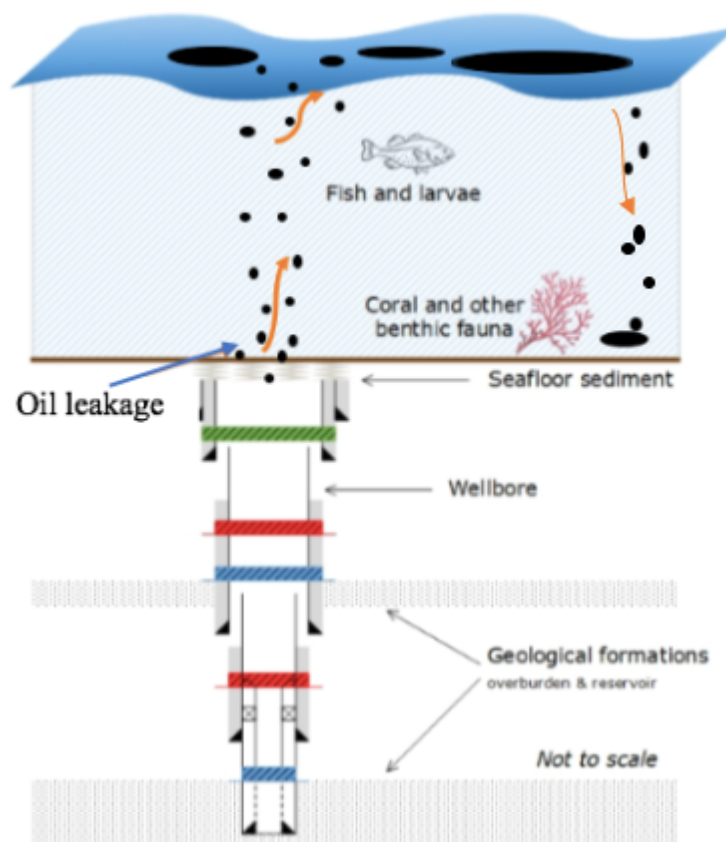


Figure 1.1: Possible interactions between abandoned wells and the marine environment, edited based on (DNVGL, 2016)

The environmental fate and effects of an oil release on exposed organisms are determined by the type of oil and the marine environmental conditions at the time of the release and the extent of biological exposure to the oil as well (Fingas, 2011; Xiong, Reed, & Ekrol, 2000). Predicting and estimating the consequences of adverse environmental impacts through a modelling approach will play a key role in evaluating and monitoring the environmental risk, which is a combination of evaluation of hazard and exposure (M.G.D. Smit, 2005; Muralikrishna & Manickam, 2017).

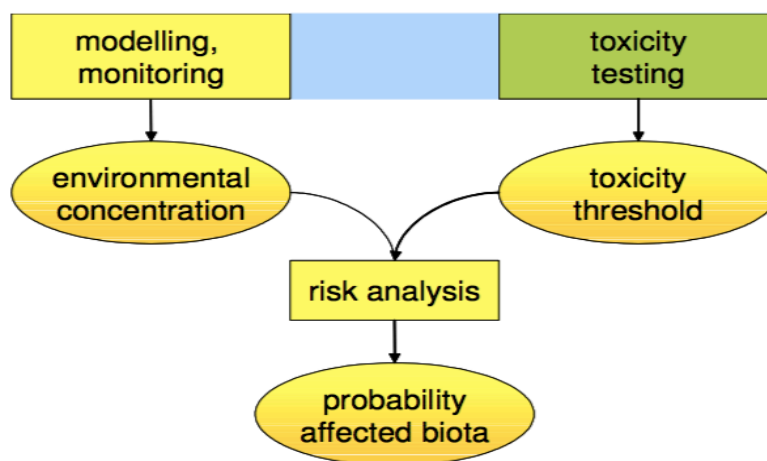


Figure 1.2: Modelling approach in environmental risk assessment (M.G.D. Smit, 2005)

When it comes to oil leakage from abandoned wells, an oil leakage model including physical fate and biological effects modules could be used as a helpful tool to simulate the future locations and states of the oil, as well as predict potential effects of the leaked oil on the marine ecosystem under realistic scenarios (Fingas, 2011; Reed et al., 1999). Based on ecotoxicity data and toxicity threshold, modelling of environmental consequences can forecast the extent of impacted marine areas and environmental concentrations by time that aquatic biota can be exposed to. Modelling results are then useful for environmental risk assessment and risk monitoring, as well as oil pollution preparedness and response planning to protect the marine environment. Additionally, results of model predictions and analyses have recently been considered to influence environmental regulation and policies at both national and international levels (National Research Council, 2007).

As a matter of fact, a variety of petroleum wells on the Norwegian Continental Shelf (NCS) are reaching the end of their productive lifespan and needed to be abandoned (Oil & Gas UK, 2016). Certainly, petroleum activities including well plug and abandonment on the NCS have complied with the international and national legislations and regulatory requirements to work

towards a mitigation of the environmental impact down to a “zero discharges” target. According to the Norwegian Petroleum Act., operators on the NCS are asked to issue a decommissioning plan, which includes an environmental risk assessment (ERA) regarding the ceasing production (NORSOK, 2013; Oil & Gas UK, 2016). Companies operating on the NCS must conduct environmental monitoring of a large extent every three years “in order to obtain information on the actual and potential environmental impacts and give authorities a better basis for regulation” (Norwegian Environment Agency, 2015). A comprehensive environmental risk assessment requires an integration of laboratory and monitoring data with fate and exposure model predictions (EC-TGD, 2003).

There are several oil spill model methods used worldwide, however, it becomes challenging when it comes to continuous oil leakage at low rate from abandoned wells under the typical conditions of the NCS as there is a shortage of knowledge and empirical data. Besides that, modelling of fates of oil release from abandoned wells on the NCS has started discussing in a previous master thesis at the University of Stavanger (Tveit, 2018). However, environmental effects of oil leakage have not yet been appropriately computed and evaluated under field conditions. There was no focus on biological exposure and effects of the oil and its hydrocarbon components, namely that how chronic risks to aquatic species can be estimated; and to what extent the impacted areas can be simulated and predicted.

Thus, concerns regarding the importance of modelling oil leakage from abandoned wells on the NCS is essential to be further emphasized.

This master’s thesis will therefore be developed with a title «**a modelling study of environmental fate and effects of oil leakage from abandoned wells**». The oil leakage from abandoned wells can be defined as continuous oil release at low flow rate over a long period of time. The thesis focuses on *modelling environmental consequences in terms of chronic biological exposure and effects by continuous low-rate oil leakages*.

1.2 Definitions in context concerning thesis topic

The modelling of an oil spill or leakage refers to execution of different model modules, data input, release information and environmental conditions to predict future locations of the oil and forecast the potential effects on the environment (Fingas, 2011).

Features (featured contents) of an oil leakage modelling system can be defined as in Figure 1.3, in which biological exposure and effects model, and continuous release spill at low rate are highlighted regarding the thesis topic.

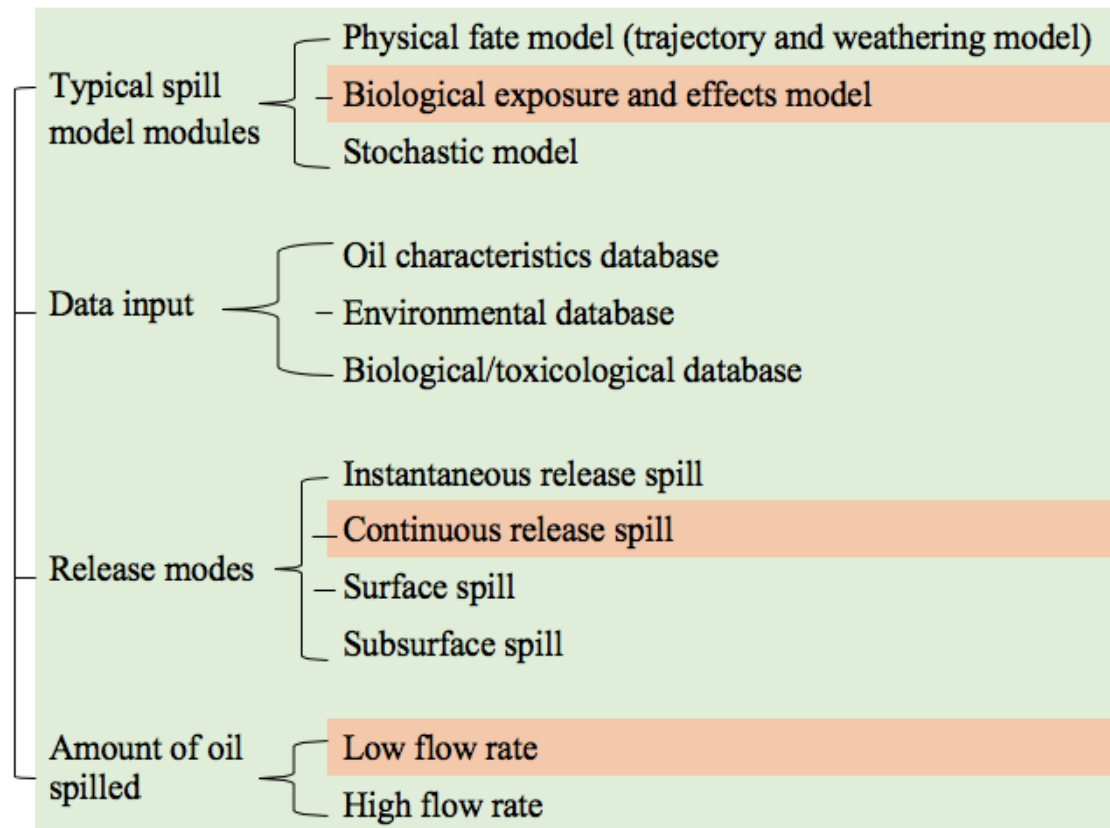


Figure 1.3: Features (featured contents) of oil spill modelling

Where:

- A biological exposure and effects model module can evaluate potential effects on exposed organisms based on results from a physical fate module. The exposure and effects are presented as areas or volumes affected; dose or concentrations of chemical compounds by time that aquatic biota exposed to them; exposure of fish, algae and other planktons; chronic effects with bioaccumulation and adaptation (Xiong et al., 2000).
- Chronic exposure refers to prolonged or repeated exposure.
- Chronic effect (long-term effect) can be defined as adverse effect on exposed organisms with symptoms that develop slowly, due to long and continuous exposure to low concentrations of a hazardous substance. It can have long-term life-changing, adaptation or potentially fatal health implications, which may not subside even when

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the exposure stops (National Research Council, 2003a, 2003b; Nordic Council of Ministers, 2007).

- Continuous release spill refers to those spills in which oil is added at the source at a relatively constant release rate in a steady state over a long period of time (French-McCay, 2004).
- Leakage flow rate: according to API RP 14B, the maximum allowable leakage is 0.4 liter per minute for liquid leakage; and allowable leakage is 15 Scf/min or 0.42 m³/min for gas leakage through closed subsurface safety valve system (American Petroleum Institute, 2005).

1.3 Previous studies

An introduction to previous studies provides a better insight on the thesis topic and its aims, and also build up theoretical frameworks.

1.3.1 Previous master thesis

The previous master thesis published by Mari Tveit in spring 2018 was titled «Understanding leakage rates in permanently abandoned wells by studying natural hydrocarbon seepage» (Tveit, 2018). The author studied natural seepages and made a comparison between leakage rate from abandoned wells and the natural seeps. Also, the OSCAR model to simulate fate of the oil leakage and impacts of hydrocarbon components in zone divisions was used. It was concluded that the leaked oil is persistent in the environment and travels over large distance at very low oil concentration in the water column due to high level of dilution and dispersion.

1.3.2 Available relevant literatures

Utilizing as starting points for the thesis study, previous literatures include considerations of:

- Potential oil leakage from abandoned wells on the NCS;
- Marine environment receptors;
- Physical fate of oil leakage in the marine environment;
- Biological exposure and effects of oil leakage;
- Bioavailability and bioaccumulation;

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- Toxic concentrations (e.g. No Observed Effect Concentration - NOEC), Predicted No-Effect Concentration (PNEC) and Predicted Environmental Concentration (PEC) in risk assessment;
- Available models in physical fate and biological effects;
- Environmental legislation and regulation.

Moreover, published research is also referenced to explain various software methods that can be applied for simulations of environmental consequences of oil leakage from abandoned wells.

Table 1.1

Literature availability associated with modelling for oil spill from abandoned wells. (+) refers to available information that can be obtained from literatures and (?) means lack of information.

Key word		Marine discharge	Oil spill	Oil leakage from abandoned well	Natural oil seep
Category					
Environmental regulation		+	+	?	
Environmental risk assessment		+	+	+	+
Leakage model	Stochastic (numerical) model	+	+	+	+
	Physical fate model	+	+	+	?
	Biological effect model	+	+	?	?

Table 1.1 points out that among other things, in addition to environmental regulation, the biological effect model for oil leakage from abandoned wells needs to be studied and this implies an inquiry to open new research trends on the NCS.

1.4 Aims and objectives of the thesis

This thesis focuses on systematical investigation of applicable model(s) that can show the fate and effects of the oil in the marine environment on the NCS. It is targeted at estimations of biological exposure and effects as a result of continuous oil leakage from abandoned wells.

The research is carried out under the current circumstance of the ongoing development of well plug and abandonment activities on the NCS while environmental regulatory requirements are

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still in need to be issued. Additionally, there have been knowledge gaps of modelling environmental consequences of leakages from abandoned wells. This thesis research aims to provide an approach to modelling biological exposure and effects that can be considered a new research trend in evaluating environmental risk of leakages from abandoned wells. The results will be used to provide recommendations to petroleum management and environmental regulation to improve the quality of the marine environment regarding permanent well plug and abandonment.

The thesis objectives include:

- *Investigation of applicable model(s)* that can predict environmental fate and effects by continuous low-rate oil leakages from abandoned wells. Available modelling methods in the literatures are reviewed.
- *Specific scenario modelling*, which is included considering oil leak case studies under conditions of the NCS.
- *Estimation of biological exposure and chronic effects* to understand potential environmental consequences and chronic risks of the oil leakage from abandoned wells.

1.5 Structure of the thesis report

The thesis's contents contain the introduction, theoretical literature review, research methods, results of modelling, discussion and conclusion, which are allocated into associated chapters. They are outlined as follows:

- Introduction
Chapter 1 presents the background, scope and schematic outlines of the thesis.
- Theoretical literature review
Chapter 2 is an overview of potential oil leakage from abandoned wells to environmental receptors on the NCS and the relevant regulatory requirements.
Chapter 3 is a review of environmental consequences and influence factors on fate and effects of crude oils in the marine environment.
Chapter 4 presents exposure and effect concentrations in risk assessment
- Research Methods
Chapter 5 mentions the literature-based research method, including investigation of applicable model(s).

Chapter 1

Chapter 6 describes the modelling method regarding scenario parameters.

- Results and discussion

Chapter 7 provides the setting up of simulations and issues the modelling results to discuss about potential impacted areas, possible chronic effects for the water column and hydrocarbon contributions to risks.

- Conclusions

Chapter 8 gives conclusions of the modelling study and recommendations to future researches.

Theoretical literature review

Academic literatures are referred as theoretical framework to make assumptions and ideas in order to set the context and direction for the research (Blaikie, 2010).

The theoretical literature reviews in chapters 2, 3 and 4 are utilized as a starting point to develop research questions, produce a foundation for interpreting experiment data by modelling and make assumptions for findings and analysis.

The information and data collected from literatures include:

- An overview of potential oil leakage from abandoned wells on the NCS, the marine environment receptors and regulatory requirements for petroleum activities on the NCS;
- Review of environmental consequences and influence factors on fate and effects of oil leakage from abandoned wells to the marine environment;
- And exposure and effect concentrations in risk assessment.

2. Potential oil leakage from abandoned wells to the environment on the Norwegian Continental Shelf

2.1 Status of abandoned wells on the Norwegian Continental Shelf

The NCS consists of three areas: the Norwegian Sea, the North Sea and the Barents Sea. The drilled wells of about 82% are most located at the North Sea section (Norwegian Petroleum, 2019).

When it comes to a cessation of production, a plug and abandonment (P&A) process is required to isolate the reservoir fluids within the wellbore and from the surface or seabed (DNVGL, 2016; Oil & Gas UK, 2016). A well is temporarily abandoned if it can be reused, re-entered or will be permanently abandoned in the future.

Table 2.1

Number of plug and abandonment wells 2016 to 2025 in the Norwegian Continental Shelf (Oil & Gas UK, 2016)

Norwegian North Sea	361
Norwegian Sea	1
Barents Sea	No activity

It is estimated that approximately 800 of the 3,800 wells have already been abandoned, and about 362 wells are expected to be decommissioned during the period 2015 - 2025 on the NCS (Oil & Gas UK, 2016). Plans for P&A activities by year to 2025 on the NCS is presented in Figure 2.1.

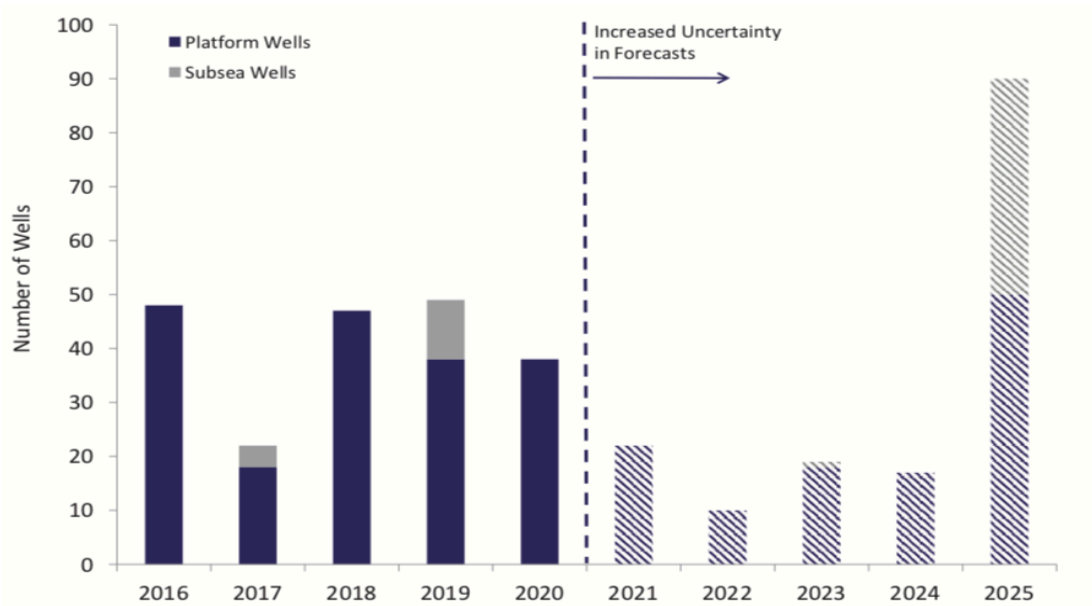


Figure 2.1: Plug and abandonment activities till 2025 on the Norwegian Continental Shelf (Oil & Gas UK, 2016)

Approximately 20-30% of wells on the NCS have experienced at least one leakage during their lifetime (Randhol & Cerasi, 2009). Furthermore, according to PSA survey in 2014, out of 282 temporarily abandoned wells on the NCS, many of them have been abandoned for over 40 years and 47% of them had integrity problems (Gundersen, 2014).

2.2 Potential oil leakage from abandoned wells

Oil leakage from an abandoned well is likely to occur along the concentrated pathways: faults, fractures and wells. The failures of well integrity and barriers, or poorly plugged wells can provide leakage pathways for oil fluids to move up the well, through corroded casing or formations and potentially into the environment. Additionally, under the natural leakage pathways through faults or fractures and geologic formations/overburden, there is potential for slow, localized leakages from the reservoir into the groundwater aquifer over a long period of time.

2.2.1 Scenario of oil leakage from abandoned wells

The oil fluids leak from abandoned well area by scenarios as below:

- Leakage through the well into aquifer or surface;
- Leakage through a defect in sealing of cap;

- Leakage through active fault/fracture due to pressure increase/induced seismicity;
- Leakage through lack of geochemical trapping, e.g. permeable overburden.

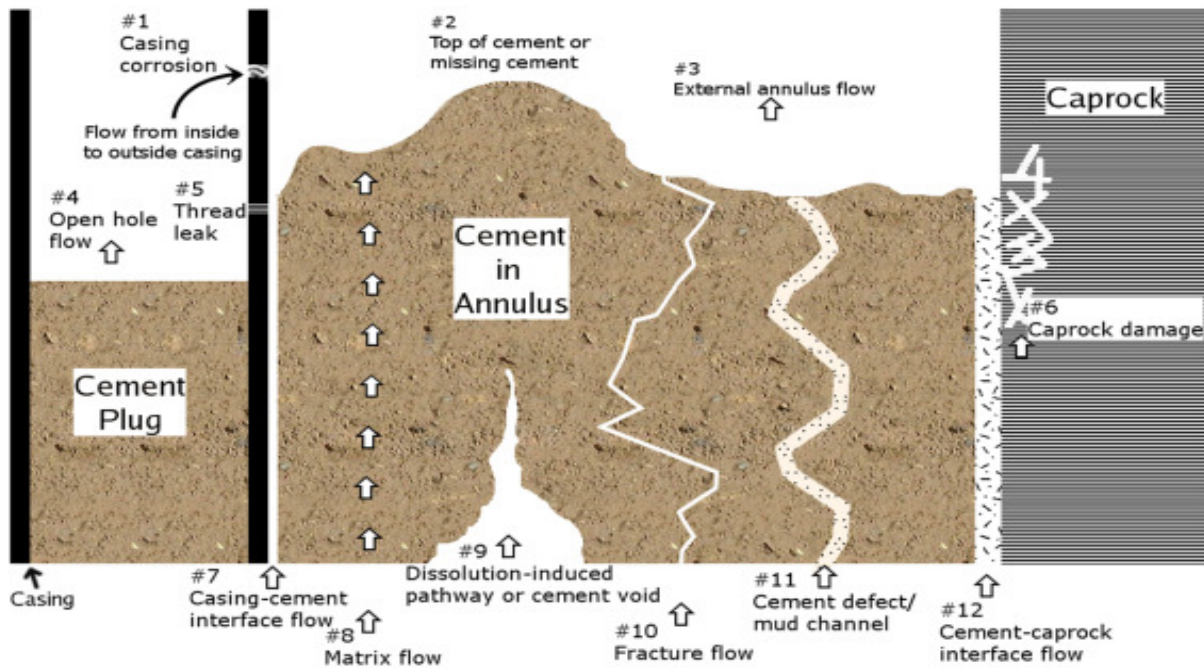


Figure 2.2: Principle oil leakage pathways from an abandoned well (J. Davies et al., 2014)

Through cemented wellbore, the oil flows between cement and surrounding rock formation or casing into production interval (layers); between cement annulus; between plugs; between casing and plug; across the cement outside the casing and then between this cement and the casing; and along the shear wellbore (ibid.).

Thus, oil fluids may leak at low rate and move slowly along the leakage pathways up to the surface over a long period at relative steady state (EPA, 2018).

2.2.2 Lessons from natural oil seeps

Crude oils also naturally release from fractures in the seafloor or rises up through eroding sedimentary rock, in the same way that a freshwater spring brings water to the surface. These seeps likely have been leaking continuously at very low rate for thousands of years and are called natural oil seeps (National Research Council, 2002).

The general geological structural type, the stage of sedimentary basin evolution, and the area of exposed rock can be factors in determining the number and rate of seeps in an area (ibid.). Possible scenarios of oil seeps would be buoyant fluids migrating slowly to the surface

through available migration pathways, such as along active fractures and fault, and through permeable formations because the pressure gradients exceed the capillary pressure (Judd & Hovland, 2009).

Considering low leakage rate, the total amount of natural oil seeps entering the marine environment is estimated as about 0.25 million tons per year and it may range from 0.025 to 2.5 million tons per year (Kvenvolden & Harbaugh, 1983). The natural seeps of crude oil worldwide are considered to be the biggest source of continuous oil releases in the ocean over long periods, occupying 47 % of the annual load to the world's ocean (Kvenvolden & Cooper, 2003). The natural oil seeps can be utilized to understand the effects of oil contamination (National Research Council, 2003b).

2.3 Marine environmental receptors

The habitats for living organisms around an abandoned well may be formed by benthic invertebrates, fish and plankton, which are either mobile or fixed (DNVGL, 2016). The surface casing of abandoned wellbores is cut off below the seafloor. Soft sediments below the seabed that contain organic debris can be collapsed by surface casing removal and then natural seepage may be dispersed through the sediment. The abiotic factors of the marine water, such as water depth, ocean currents, sea water salinity, temperature and type of sediments on the seafloor can vary from place to place.

With regard to biological environment on the NCS, the marine waters of 1,383,000 km² in Norwegian Sea, 1,400,000 km² in Barents Sea and 570,000 km² in North Sea are very productive and home to a rich variety of species, from cold-water corals to large fish stocks, seabirds and marine mammals. The food chain seems to be quite similar in the Barents, Norwegian and North seas. Zooplankton, pelagic fish and squid have higher biomass in the Norwegian Sea, while marine mammals and seabirds have higher biomass in the Barents Sea (Forsgren, 2009).

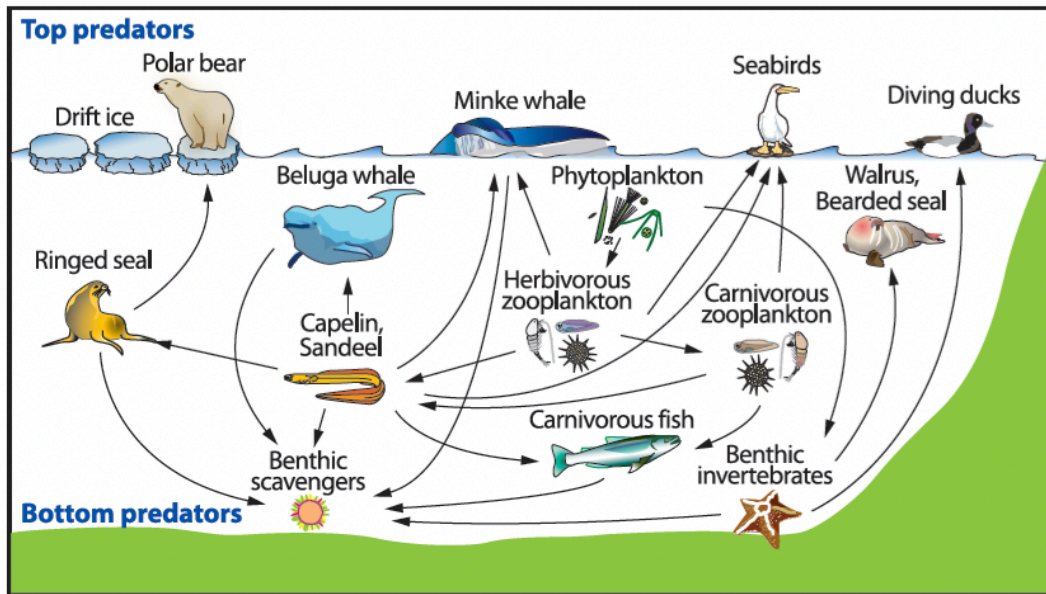


Figure 2.3: Food web in the Barents Sea in the Norwegian Continental Shelf (AMAP, 2007)

Plankton, mostly diatoms, is the most important basis for the food chains of the seas on the NCS. Zooplankton species, mainly amphipods, *Calanus* and copepods act as an important link between phytoplankton and higher trophic levels (Forsgren, 2009). Zooplankton plays a key food source for many fish stocks and marine mammals (Norwegian Ministry of the Environment, 2009).

Table 2.2

Most abundant phyto- and zooplankton species in the North Sea (Johns & Reid, 2001)

Northern North Sea		Southern North Sea	
Phytoplankton			
1.	<i>Ceratium fusus</i> .		<i>Ceratium fusus</i>
2.	<i>Ceratium furca</i>		<i>Ceratium furca</i>
3.	<i>Ceratium tripos</i>		<i>Ceratium tripos</i>
4.	<i>Ceratium macroceros</i>		<i>Chaetoceros (Phaeoceros) spp.</i>
5.	<i>Ceratium longipes</i>		<i>Chaetoceros (Hyalochaete) spp.</i>
6.	<i>Thalassiosira spp.</i>		<i>Ceratium macroceros</i>
7.	<i>Protoperidinium spp.</i>		<i>Thalassiosira spp.</i>
8.	<i>Ceratium horridum</i>		<i>Protoperidinium spp</i>
9.	<i>Chaetoceros (Hyalochaete) spp.</i>		<i>Ceratium horridum.</i>
10.	<i>Chaetoceros (Phaeoceros) spp.</i>		<i>Ceratium longipes</i>
Zooplankton			
1.	Total copepods		Total copepods
2.	<i>Calanus traverse</i>		Echinoderm larvae
3.	<i>Calanus I-IV</i>		<i>Para-Pseudocalanus spp.</i>
4.	<i>Para-Pseudocalanus spp.</i>		<i>Acartia spp.</i>
5.	Echinoderm larvae		<i>Temora longicornis</i>
6.	<i>Acartia spp.</i>		<i>Evadne spp.</i>
7.	Thecosomata spp.		<i>Pseudocalanus adult.</i>
8.	<i>Evadne spp.</i>		<i>Oithona spp.</i>
9.	<i>Oithona spp.</i>		<i>Calanus traverse</i>
10.	<i>Pseudocalanus adult</i>		<i>Podon spp.</i>

Moreover, a rich variety of fish has been found on the NCS, including mackerel, herring, blue whiting, beaked redfish, saithe. Approximately 6 million pairs of seabirds breed along the coastal mainland of Norway, including Atlantic puffin, black-legged, common guillemot, and Northern fulmar (Forsgren, 2009). Abundance of marine mammals includes species of grey seals, harbour seal, minke whales and baleen whales. Additionally, the Norway's waters have been acknowledged in some of the world's largest cold-water corals, of which over 1300 species has been found in association with cold water coral reefs that are located in a wide depth range from 40 to 3600 m (ibid.).

2.4 Legislative and regulatory requirements

The "Zero harmful discharge" regime has been implemented on the NCS in 1996 with the goal of "zero environmental harmful discharges" for the marine environment within 2005 (D. Smit, Mathijs, Frost, & Johnsen, 2011). The P&A activities on the NCS carried out in accordance with the NORSOK D-010 regulation are thus required to reach zero leakage for permanent abandonment. However, the NORSOK Standard D-010 also points out that it is not required to implement monitoring after the well is permanently abandoned.

According to the Norwegian Petroleum Act., operators on the NCS are asked to issue a decommissioning plan, which include an ERA regarding the ceasing production (NORSOK, 2013; Oil & Gas UK, 2016). The ERA for petroleum activities on the NCS are implemented to comply with relevant regulations including the ISO31000 standard (ISO 2009), NORSOK standard Z-013 (2010), regulations issued by Petroleum Safety Authority Norway (PSA), as well as the OSPAR convention (Vinnem, 2013). The 2012 OSPAR guideline also points out the involvement of ERA steps in a risk-based approach, in which the outputs of ERA are risk management and monitoring plans. The environmental monitoring for petroleum activities on the NCS is carried out in accordance with guidelines (Norwegian Environment Agency, 2015).

Moreover, the petroleum activities on the NCS are required to follow chemical management regulations. The Harmonised Offshore Chemical Notification Format (HOCNF) is provided by OSPAR Decision 96/3 to standardize the requirements for testing and reporting all of chemicals in offshore petroleum operations within the North Sea and the northeast Atlantic. As a result, offshore chemicals in Norway are categorised into 4 colour code groups of black,

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red, yellow and green based on their toxicological hazards. These group chemicals are described as follows:

- Discharge of black group chemicals is not permitted,
- Yellow group chemicals need a discharge permission,
- Red group chemicals need a discharge permission, but they have to be phased out,
- While green group chemicals are considered to pose little or no risk to the environment and are allowed to be discharged without permission.

3. Environmental consequences: influence factors on fate and effects of oil leakage

Toxic effects to individual aquatic organisms are evaluated for uptake of chemical compounds of the oil from sea water or food ingestion as species are exposed to oil droplets by contact with body surfaces or by food uptake (Olsen et al., 2013).

The environmental exposure and effects of oil leakage to marine organisms depends on several factors, including concentration of hydrocarbons, length of exposure, persistence and bioavailability of specific hydrocarbons, the ability of organisms to accumulate and metabolize various hydrocarbons (Capuzzo, 1987). The fate and effects of an oil leak are determined by the type of oil (e.g. hydrocarbon components and droplet sizes) and the environmental conditions (e.g. wind and current) (Fingas, 2011).

3.1 Considerations of crude oil compositions

Crude oil is a mixture of thousands of different hydrocarbons, generally in the liquid state, that may also include compounds of sulfur, nitrogen, oxygen, and metals and other elements. The hydrocarbons present in crude oils are classified into three general types: linear alkanes (paraffins or aliphatics), cyclic alkanes (naphthene) and aromatics, which vary considerably within oils (Jane Øksenvåg et al., 2018). They are also divided in four chemical group classes, namely saturates, aromatics, resins and asphaltenes.

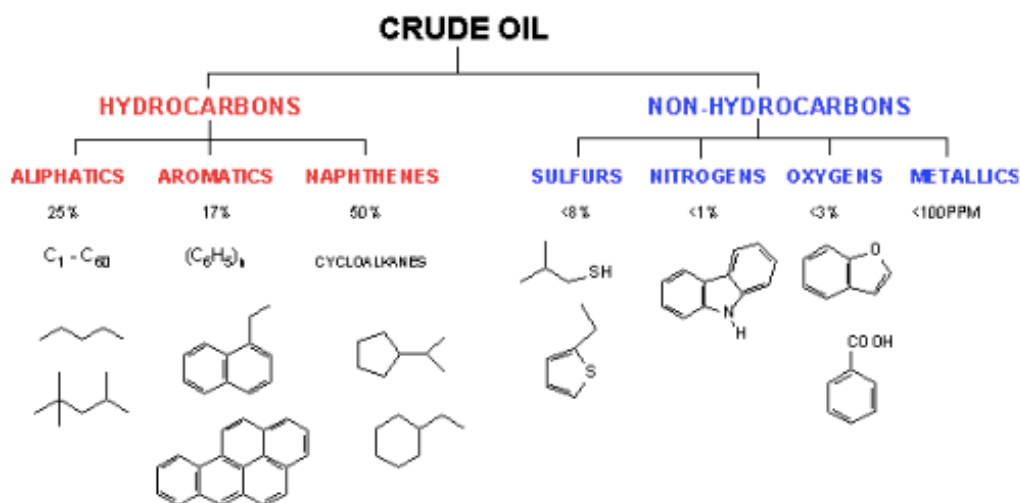


Figure 3.1: Compositions of crude oil (Dickneder, 2019)

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The saturates consist of linear (*n*-alkanes), branched (*i*-alkanes) and cycloalkanes (naphthene). The most abundant one-ring (monocyclic) aromatic hydrocarbons are BTEX (benzenes, toluenes, ethylbenzenes, xylenes). Those with more than one-ring compounds are commonly referred to as polycyclic aromatic hydrocarbons (PAHs). The most common aromatic hydrocarbon with two rings is naphthalene. Other commonly groups include three-ring phenanthrene, dibenzothiophene and fluorene. Resins are components with highly polar end group and long alkane tails, made up of aromatic and naphthenic rings and heteroatoms such as oxygen, sulfur and nitrogen. Asphaltenes are large highly polar components of condensed aromatic and naphthenic rings and heteroatoms.

Short branched alkanes (C5 – C10) and monoaromatic compounds like BTEX can mostly lost by the surface evaporation processes depending on temperature and wind speed (Jane Øksenvåg et al., 2018). BTEX consists of highly water soluble and volatile compounds, while naphthalenes are less volatile and soluble compared to BTEX. The other more complex compounds are also likely very resistant. In term of biodegradation, depending on their hydrogen (H) and carbon (C)- structures, the oil compounds are expected to be degraded by micro-organisms in the seawater following in order: straight-chain *n*-alkanes > branched isoalkanes > cyclic alkanes > cyclic naphthenes > aromatics > resin > asphaltenes (Perry, 1984). Under the anaerobic conditions prevailing during formation of the oil sands, the saturated hydrocarbons are mostly biodegradable, the aromatic hydrocarbons are much less biodegradable and the resins and asphaltenes are not at all (ibid.).

When it comes to environmental effects, among the compounds of crude oils, *n*-alkanes, BTEX and (PAHs) are most environmentally concerned regarding their persistence in the marine environment and their degradation products in sediments and cold environments (Jane Øksenvåg et al., 2018). BTEX are neurotoxic to attack organisms, in which benzene and toluene have been found to be carcinogenic to mammals. The medium and high molecular weight aromatic hydrocarbons, e.g. PAHs, can result potentially chronic effects on aquatic organisms as they are among most persistent compounds in both animal tissues and sediments (National Research Council, 2003a). PAHs are considered to be the most toxic components of crude oil and they are also associated with potential carcinogenic and mutagenic effects in aquatic animals (ibid.).

3.2 Bioavailability and bioaccumulation

The concept of bioavailability and bioaccumulation are extremely important in understanding and describing the environmental fates and biological effects of the oil in the marine environment (National Research Council, 2003b).

3.2.1 Bioavailability

Accumulation of the oil hydrocarbons by marine organisms depends on the biological availability of hydrocarbons, the length of exposure, and the organism's capacity for metabolic transformations. Bioavailability can be defined as “the extent to which a chemical can be absorbed or adsorbed by a living organism by active (biological) or passive (physical or chemical) processes” (Kleinow et al., 1999).

Bioavailability is measured as log bioconcentration factor (log BCF), in which BCF is a ratio of concentration of substances in tissues (C_f) and concentration in water (C_w) at equilibrium:

$$BCF = C_f/C_w$$

Those concentrations are obtained from bioconcentration of the substance from the water phase and as a result of bioaccumulation from the food the aquatic organisms (zooplankton, fish) consume (EC-TGD, 2003). Bioconcentration is defined as the net result of the uptake, distribution, and elimination of a substance in an organism due to waterborne exposure, whereas bioaccumulation includes all routes of exposure (i.e. air, water, food) (IRIS-Biomiljø, 2011).

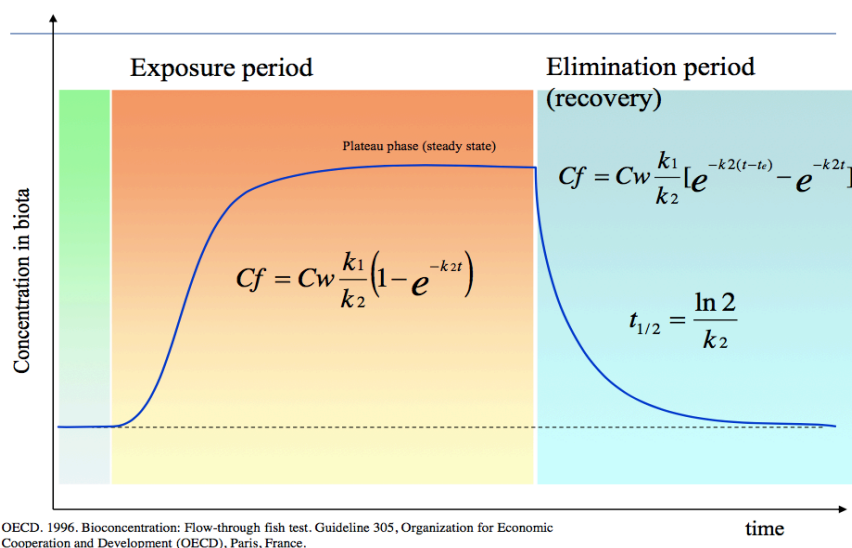


Figure 3.2: Bioconcentration in biota over time (OECD, 1996)

Bioavailability depends on the physical or chemical properties of the chemical in contact with the organism and the ability of the organism to excrete or detoxify the chemical (Neff, 2002). Toxins that organisms expose to, if with a more amount than the body can eliminate, will accumulate in fatty tissue and organs. The greater the accumulation, the greater the stresses on the organism health. The measurement of bioavailability should include steady state body burden, efficiency of pollutant uptake and the rate of uptake (Feijtel et al., 1997).

3.2.2 Equilibrium partitioning theory and coefficient K_{ow}

The uptake of an organic substance is driven by its hydrophobicity (National Research Council, 2003b). With respect to the oil in seawater, oil hydrocarbons contain nonpolar (hydrophobic) organic compounds that have a low aqueous solubility and a high lipid solubility.

According to the equilibrium partitioning theory, when an aquatic animal is exposed to a nonpolar organic chemical dissolved in the water, the chemical partitions across permeable membranes into tissue lipids until an equilibrium. When the concentration of nonpolar organic chemicals in the tissues reach a critical concentration, toxic actions occur in the organism (McCarty & Mackay, 1993). This equilibrium partition or hydrophobicity of hydrocarbon compounds can be displayed by the octanol/water partition coefficient for the substances (K_{ow}) as octanol is a non-polar fatty alcohol that is insoluble in water and is hydrocarbon-like (Davies & Dobbs, 1984).

The octanol/water partition coefficient (K_{ow}) is defined as the ratio of the concentration of a chemical in n-octanol and water at equilibrium at a specified temperature.

K_{ow} = Concentration of a chemical X in octanol/concentration of X in water (ibid.).

$$\text{Log } K_{ow} = \log \left[\frac{[X]_{\text{octanol}}}{[X]_{\text{water}}} \right] \text{ (Davies \& Dobbs, 1984)}$$

Log K_{ow} describes the tendency of a chemical to solve in an artificial biotic lipid (i.e. octanol) compared to the solubility in water. Thus, log K_{ow} is a relative indicator of the tendency of an organic compound to be adsorbed into organisms. The distribution of the oil compounds between water and octanol is used to determine the toxicity of the compounds to a living organism. In general, log K_{ow} is the inverse of water solubility and directly proportional to molecular weight of a substance.

3.2.3 Effects of log K_{ow} on the bioaccumulation/bioconcentration potential

Log K_{ow} coefficient together with the bioconcentration factor (BCF) are used to assess the bioaccumulation potential.

$$\log \text{BCF}_{\text{fish}} = 0.85 \cdot \log K_{\text{ow}} - 0.70 \quad (\text{EC-TGD, 2003})$$

The smaller the log K_{ow}, the more soluble the substance is in water. Also, the higher the logK_{ow} is, the more soluble the substance is in fatty (nonpolar) substances. LogK_{ow} can be used to predict how quickly the tested chemical will accumulate in organisms. The more fat-soluble the chemical, the more it will accumulate (e.g. in fatty tissue) and therefore in the environment. Water-soluble substances are more readily eliminated and generally have a lower bioaccumulation potential (ibid.).

Log K_{ow} is an important parameter to forecast the distribution of a substance in various environmental compartments (water, soil, air, biota, etc.) (EC-TGD, 2003). It says logK_{ow} is a factor of a Quantitative Structure Activity Relationship (QSAR) which is used to predict BCF of highly hydrophobic chemicals to help in risk assessment of a chemical since log BCF reflects the bioaccumulation potential of a chemical. QSAR establishes relationships between physical or chemical properties of a chemical and its environmental properties. It presents the BCF and the toxicity of environmental pollutant chemicals.

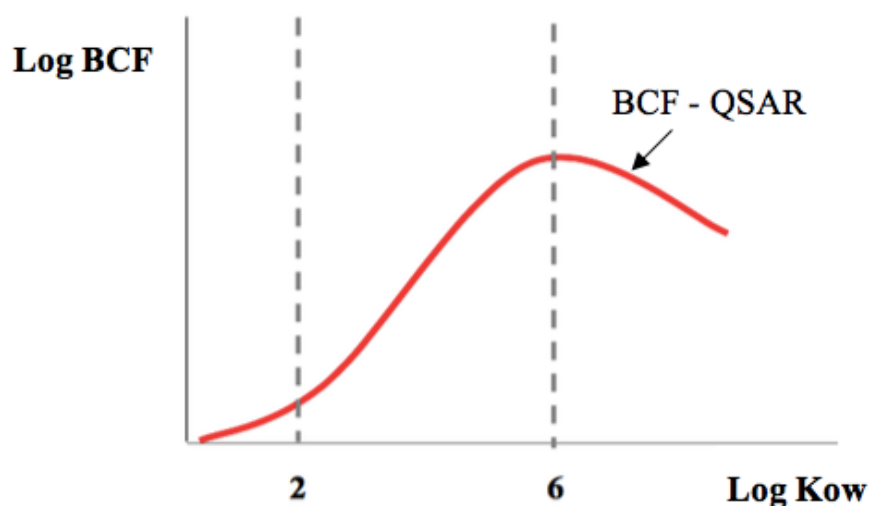


Figure 3.3: A Quantitative Structure Activity Relationship (QSAR) approach for assessing the bioaccumulation potential of organic chemicals (Pampanin, 2018)

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For chemicals with hydrophobicity within the range $\log K_{ow}$ of 2 to 6, there exists a nearly linear relationship between the hydrophobicity and the bioconcentration potential. Substances with high $\log K_{ow}$ values tend to adsorb more readily to organic matter because of their low affinity for water. Chemicals with very high $\log K_{ow}$ values (i.e. > 4.5) are of greater concern because they have high potential to bioconcentrate in living organisms (European Chemicals Agency, 2017). Also, $\log K_{ow}$ values greater than around 6.0 relate to reducing bioconcentration potential in organisms.

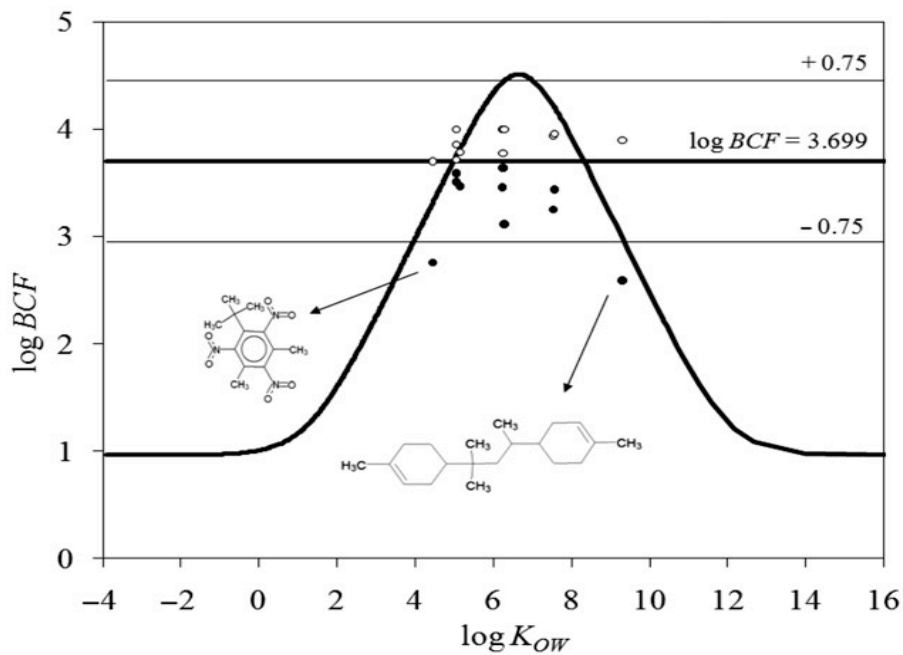


Figure 3.4: The octanol/water partition coefficient ($\log K_{ow}$) and bioconcentration for different molecular weights (Dimitrov et al., 2012)

The $\log K_{ow}$ of hydrocarbons increases with increasing molecular weight. By equilibrium partitioning theory, however, the higher molecular weight of hydrocarbons are less bioavailable than predicted because of limitations on their uptake rates by organisms, their lower solubility in tissue lipids, and rapid metabolism of higher molecular weight in some marine animals (Neff, 2002).

The EC TGD (2003) states that with low K_{ow} values (< 1000), chemicals are assumed to dissolve in the water column. For large K_{ow} values (≥ 1000), chemicals are assumed to deposit on the sea floor. Chemicals that are not (or negligible) water soluble ($K_{ow} \geq 1000$) are assumed to accumulate in the sediment on the sea floor. Impacts in the water column from these chemicals (i.e. heavy metals) are neglected (ibid.).

3.3 Oil droplet size distribution

According to (Delvigne & Sweeney, 1988), the oil broke up into different oil droplets due to the effect of breaking waves on the surface or turbulence in the water column. Natural oil seeps are normally identified as tiny and black globules with the range of 1 to 10 mm diameter droplets and typical diameter of 5 mm (Mikolaj, Allen, & Schlueter, 1972).

The rising velocity of an oil droplet is proportional to the oil droplet diameter according to Stokes' law.

$$v = \frac{gd^2(\rho_1 - \rho_2)}{18\eta}$$

Where: v = rising velocity of the oil droplet; g = gravitational constant; d = oil diameter;

ρ_1 = density of the sea water; ρ_2 = density of the oil and η = the viscosity of the water

According to the Stokes' law, the larger the size of an oil droplet, the larger the square of its diameter, then the greater its rising velocity will be. Thus, larger droplets float upwards faster than smaller ones do. The droplets larger than 5 mm can reach the surface within hours, while it takes around 24 h or more for the smaller ones rising up to the surface (Tveit, 2018). Larger droplets will be more quickly to reach the surface where the oil weathering process including evaporation and oxidation happen, while smaller droplets with large surface area to volume ratio will be more likely to dissolve in the water column.

After an oil release, small crude oil droplets moved by waves and winds are effectively suspended in the water column (Delvigne & Sweeney, 1988). Small particles suspended in a fluid are subjected to Brownian diffusion and turbulent diffusion (Ounis & Ahmadi, 1990). The turbulent diffusion is dominant for particles larger than 5 μm (ibid.). With very small diameter droplets of 1 to 1000 nm, the high-viscosity crude oil could be transformed into oil-in-water emulsion and Brownian motion may keep them suspended (Wolfe, 2013). The droplets of 1 μm to more than 1000 μm (or 1mm) are created by water turbulence which strips away globules from the slick, according to (Thibodeaux, 1996). Settling and turbulent diffusion (dispersion) drags the droplets down and the droplets are kept suspended in the water column (ibid.).

When small oil droplets are suspended in the water, they can easily interact with planktonic organisms and be ingested by zooplankton (protozoan and metazoans) or attached to

phytoplankton (Almeda et al., 2013). Moreover, smaller droplets find more easily absorbed and degraded by oil-degrading bacteria than the larger droplets do due to their higher surface area relative to volume of oil and their more effective oil-water contact time by being suspended in the water column (ibid.). Then, smaller oil droplets would enhance the oil biodegradation rate.

3.4 Seasonal variation

Seasonal variation exists in the central and northern offshore areas of the North Sea (Tveit, 2018). The seasonal changes have a considerable influence on the surface and the water column properties.

Strong winds, strong currents and low temperature at the surface in winter generate vertically great mixing, the mixed layer becomes deep, generally reaching 50 m to 100 m in depth or several hundred meters in some regions, according to (Goosse, 2015). In summer by contrast, below the summer mixed layer, the temperature is insulated from the surface and gradually decreases toward the seafloor that induces the formation of a region with vertical gradients or thermocline which separates the surface layer from relatively homogenous deep waters (ibid.)

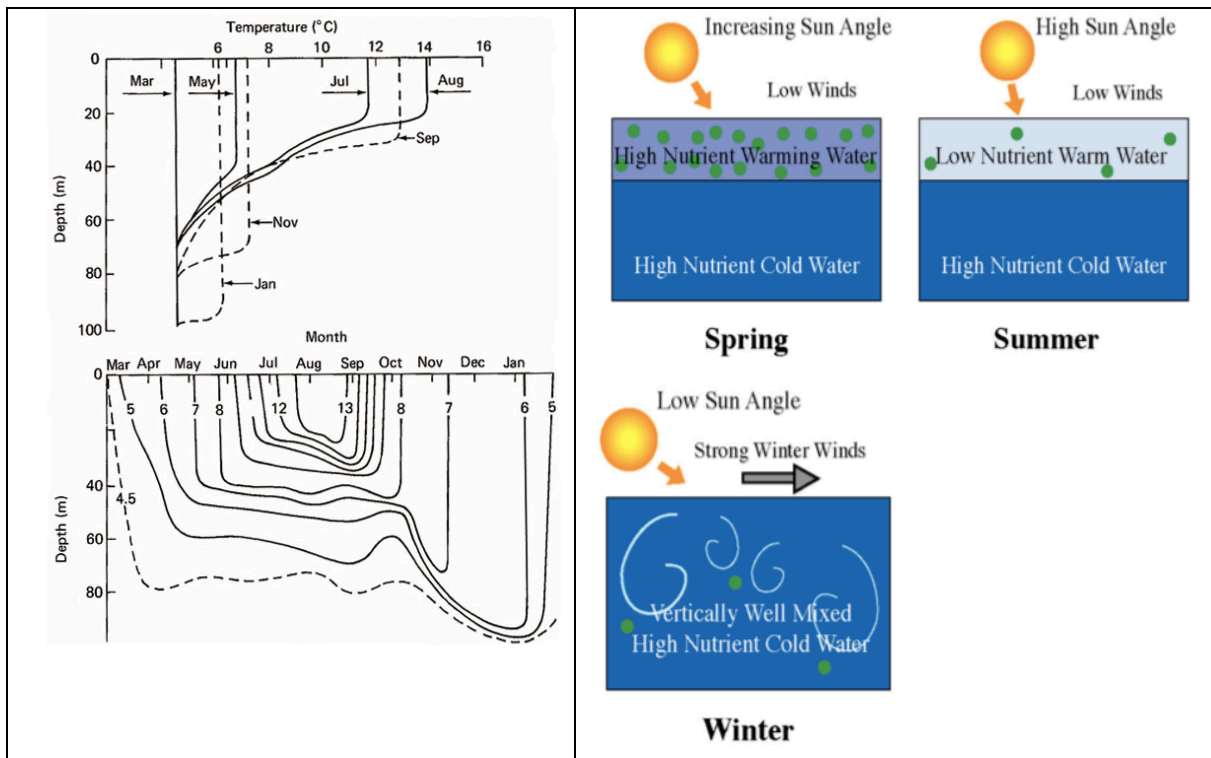


Figure 3.5: Typical seasonal variation and thermocline (Goosse, 2015)

Temperature on the surface and near surface rises in spring and summer, and the winds also tend to be weaker, resulting less mixing and the decreased density at the surface. This tends to stabilize the water column with the shallow mixed layer of maximum 40 m in depth in spring and summer (ibid.). According to (Institute of Marine Research, 2006), in the warmer water, a number of species extend their habitats; phytoplankton grow more rapidly in summer and reach its maximum during spring blooms; fishes (e.g. herring, blue whiting, cod) are able to successfully spawn and increase in size.

Due to the shallow mixed layer and high availability of light in summer, the oil chemical alteration by sunlight is highly variable, photooxidation and evaporation resulting loss of hydrocarbons become significant during summer months, and slower in winter. Vapor pressures of hydrocarbons decrease about 5% per degree centigrade at sea water temperature (Wolfe, 2013). The biodegradation rates of hydrocarbon from oils also are slower in cold waters than in warm (ibid.).

3.5 Physical fate of oil leakage in the marine environment

The fate of an oil leakage concerns the future location and states of the oil in the marine environment. They relate to a series of changes in physical and chemical properties of the leaked oil. Sizes of oil leakages vary from invisible micro-leakages on the sea floor to macro-leakages of visible oil slicks on the water surface (Pampanin & Sydnes, 2013; Tveit, 2018).

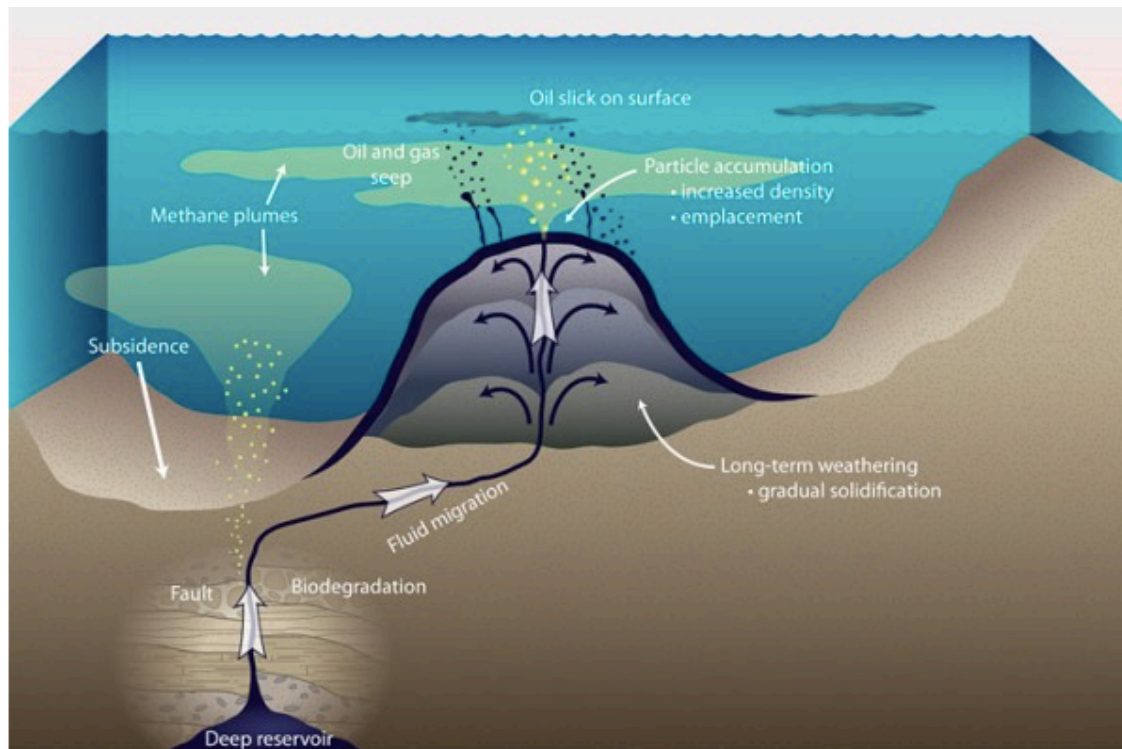


Figure 3.6: Fate of oil seeps from the seabed to the surface (Woods Hole Oceanographic Institution, 2009)

Similar to a release mechanism for an oil seep, the oil from abandoned wells enters the ocean from the seabed. The liquid oils from abandoned wells if flow out from beneath the sea floor can ascend slowly through small white chimneys and seeps through the sediments (Heiko; Sahling et al., 2016). The heaviest oil may probably settle around the crack and possibly sink back to seafloor, while the lightest oil will migrate to the surface. Since the buoyancy of the droplets increase when oil is mixed with gas and densities of crude oils (i.e. $0.7 - 0.9 \text{ g/cm}^3$) is lower than the density of the seawater (i.e. 1.03 g/cm^3), the oil will float on the surface and gradually weathered (Kvenvolden & Harbaugh, 1983).

The processes included in weathering are evaporation, emulsification, photooxidation, spreading and formation of tar balls on the surface; dispersion, dissolution and biodegradation in the water column; sedimentation and biodegradation in the sediments (Fingas, 2011).

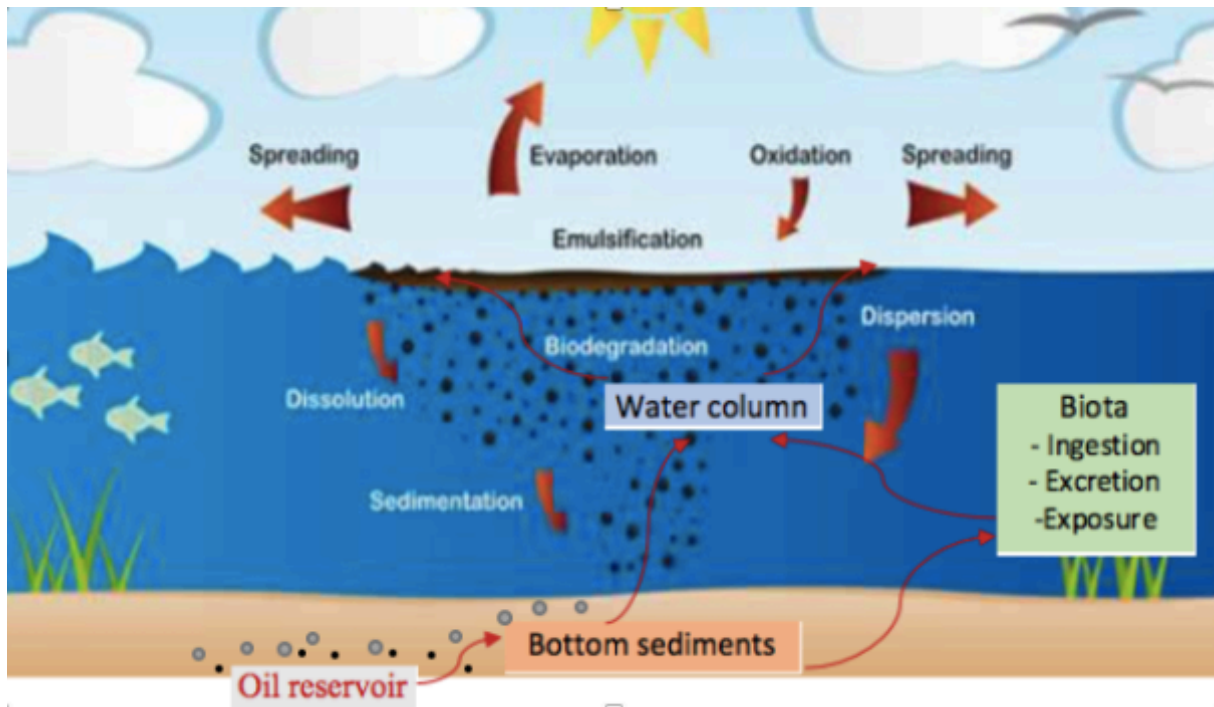


Figure 3.7: Weathering of oil in the marine environment, edited based on (ITOPF, 2014)

Weathering processes play an important role in altering the toxicity of an oil leakage by removing volatile and soluble components of the oil, including toxic aromatic hydrocarbons. According to (National Research Council, 2003a; Neff, 2002), when crude oil is exposed to sunlight and oxygen in the water column or on the surface, both photooxidation and aerobic microbial oxidation take place. Small hydrocarbon molecules up to C_{20} are oxidized before larger ones. Monocyclic aromatic hydrocarbons (e.g. benzene, toluene, ethylbenzene, and xylene) will be lost rapidly by evaporation to reduce toxicity of the oil (National Research Council, 2003b). Within hydrocarbons, the order of weathering is the aliphatic *n*-paraffins (*n*-alkanes) first, followed by branched and cyclic alkanes (naphthalenes), then the polycyclic aliphatic and aromatic hydrocarbons. Simultaneously, polycyclic aromatics PAHs become more important contributors to the toxicity of weathered oils. Oil compounds react chemically with oxygen either breaking down into soluble products or forming persistent compounds called tars which remain in the environment for years by floating on the surface and reaching beaches and shorelines (Tveit, 2018).

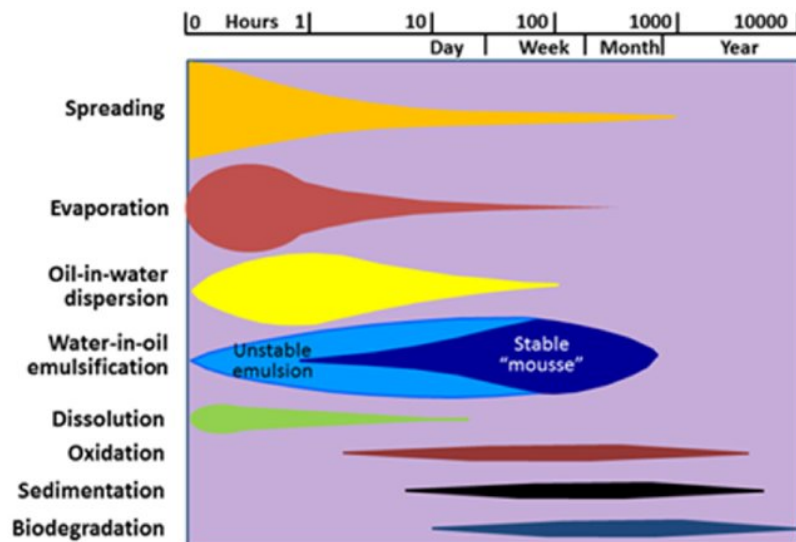


Figure 3.8: Fate of crude oil with time (Fernandes, 2018)

Figure 3.8 shows that early weathering occurs through dispersion, evaporation, dissolution and emulsification, while biodegradation, oxidation and sedimentation are a long term process, which is very slow to start, can last for thousand years and will determine the ultimate fate of the oil leaked (Fernandes, 2018).

As the oil from abandoned wells enters the ocean from the seabed, it is relatively less weathered in comparison with other source oils that the weathering occurs before the oil is deposited in bottom sediments (National Research Council, 2003a).

3.6 Potential biological exposure and effects of oil leakage

The biological effects of oil pollution are often referred to as acute or chronic. Acute effect can be the immediate short-term effect of a single exposure to a toxicant, while chronic effect is defined as either the effects of long-term and continuous exposure to a toxicant or the long-term sublethal effects of acute exposure (National Research Council, 2003b). Effects that still exist after two years should be considered as long-term (ibid.)

Chronic exposure to hydrocarbons of the leaked oil can result in alteration in reproductive and developmental potential of populations of marine organisms (National Research Council, 2003a). Through food chains in the marine environment, alterations can vary from primary producers of phytoplankton to consumers of zooplankton and eventually to top predators of fishes. The measurement of a biological effect of the oil on organisms can refer to estimation

of bioaccumulation, bioavailability and impacts on the development, growth and mortality of organisms (National Research Council, 2003a; Olsen et al., 2013). A chronic effect can relate to reduced growth, reduced reproduction, lost population, etc. (ibid.).

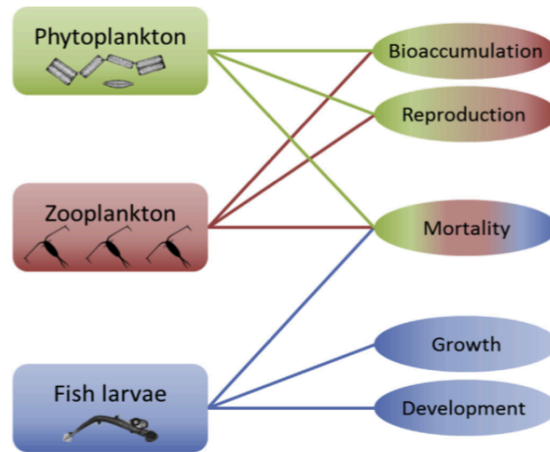


Figure 3.9: Effects endpoints for the main organism groups in an ecosystem (Olsen et al., 2013)

In regard to environmental effects of oil leakages, many studies state that the nature of nearby marine environments can be impacted considerably after being exposed to oil slicks. The oil leaks when accumulating to a certain amount can cause effects on the marine environment to some degree due to the components of PAHs, n-alkanes and heavy metals in oil (Abha & Singh, 2012; Almeda et al., 2013; Pampanin & Sydnes, 2013). Fresh oils, which are oxidized by microbes, can first serve as a supplementary food source for food webs. However at sufficiently high concentrations the aromatic components of oil, seep become toxic to marine organisms (National Research Council, 2003b). Long term exposure of *Mytilus edulis* to low concentration of North Sea crude oil can lead to adverse correlation between cellular and lysosomal properties and growth. Seabirds and marine mammals may be poisoned when they inhale toxic doses of petroleum vapor, ingest oil or prey that have oil (National Research Council, 2003a).

Otherwise, effects of natural oil seeps can be utilized to understand the effects of oil leakage from abandoned wells. With a period of thousands of years, animals living near seeps might have unique adaptations and extensively contaminated (ibid.)

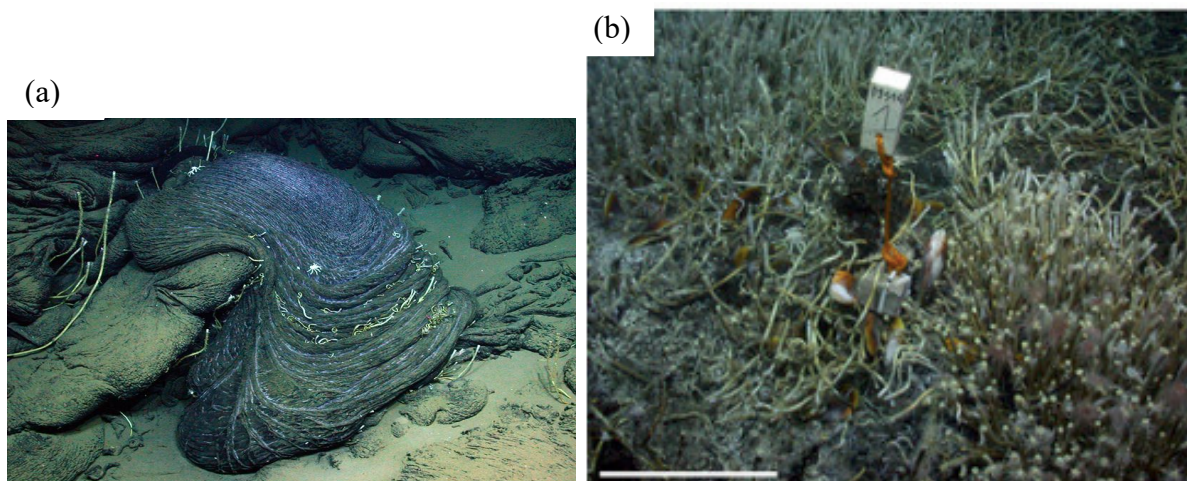


Figure 3.10 a & b: Heavy oil in about 3100 meter water depth and diversity of habitat at oil seeps on the sea floor (Heiko Sahling et al., 2016)

The presence and development of hydrocarbon eating macro-organisms or the oil degrading microbes associated with the degradation of long chain alkanes and PAHs are found in some regions of natural oil seeps (Pampanin & Sydnes, 2013). The results may be indicated through the change in population of fauna and flora in the area and sometimes in adaptation of marine organisms over generations of hydrocarbon exposure (National Research Council, 2002). For some organisms that are not adapted, the oil is obviously harmful, but asphalt on the sea floor in some cases is home to its own organisms that can even thrive on these hydrocarbons (Heiko Sahling et al., 2016).

On benthic ecosystems, at only a few cm from the active sources of seepage, the nematodes, worms and copepods form with high abundance. A diverse benthic community of mainly detrital feeders occurs within several meters of the active seeps and some *rhepoxiniid* amphipods that are sensitive to oil are found outside the seep area (Spies & Davis, 1979). At some distances from areas of active seepage, the diversity of organisms increases (ibid.).

4. Exposure and effect concentrations in environmental risk assessment

4.1 Predicted No-Effect Concentration in effect assessment

When it comes to effect assessment, PNEC is the threshold value for the environmental compartments (water, soil, sediment) or an environmentally safe concentration of a compound, at which no effects on the biota are expected and below which adverse effects will most likely not occur during long-term or short-term exposure (ChemSafetyPro, 2019; Férard & Blaise, 2013).

4.1.1 Toxicological dose descriptors

The endpoints most used for deriving PNECs are mortality (EC_{50} or LC_{50}), growth and reproduction (EC_x or NOEC). Those values derived from QSARs are established for individual hydrocarbons to express the dose-response relationship.

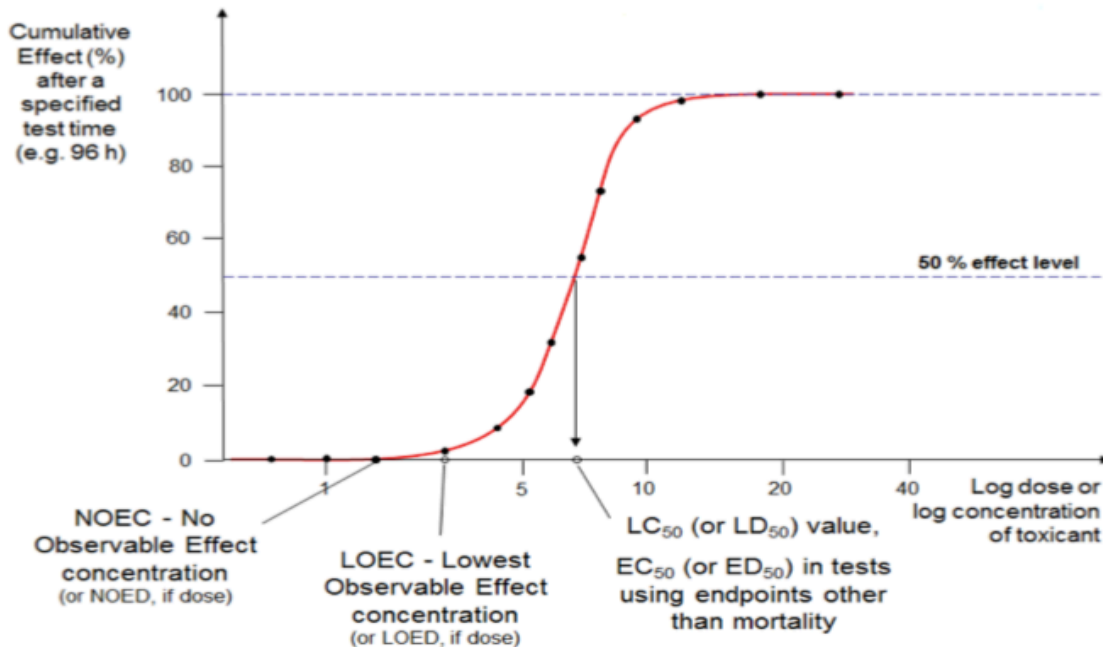


Figure 4.1: Sigmoidal cumulative dose - response curve (Pampanin, 2018)

For short-term ecotoxicology studies, EC_{50} is Effect Concentration, at which 50% of the tested effect is reached and LC_{50} is Lethal Concentration at which 50% of the tested individuals die.

For long-term ecotoxicology studies, NOEC (or dose) is the highest exposure concentration of a test chemical or toxicant that causes no observable adverse effect on the test organisms. EC_x is the concentrations at which x % (for example 10% for EC_{10}) effect was observed or derived statistically when compared to the control group (ibid.).

Table 4.1

Classification of substances according to their toxic properties (Patin, 1999)

Acute Toxicity		Chronic Toxicity	
Rating	48–96-hr LC_{50}/EC_{50} (mg/l)	Rating	No Observed Effect Concentration (mg/l)
(0) Non-toxic	>1,000	-	-
(1) Practically non-toxic	100–1,000	-	-
(2) Slightly toxic	10–100	(2) Low chronic toxicity	>1
(3) Moderately toxic	1–10	(3) Moderate chronic toxicity	0.1–1.0
(4) Highly toxic	0.1–1.0	(4) High chronic toxicity	0.01–0.1
(5) Very highly toxic	0.01–0.1	(5) Very high chronic toxicity	0.001–0.01
(6) Extremely toxic	<0.01	(6) Extremely high chronic toxicity	<0.001

The lower the LC_{50}/EC_{50} or NOEC are, the higher toxic the substances become. Thus, the lower PNEC value of the substance mean more toxic or hazardous the substance can bring to the exposure organisms.

The terms acute or chronic PNEC denote the PNEC values that have been derived from acute or chronic data, respectively. In general, acute PNEC values are lower than chronic PNECs (Vestel et al., 2016). Assessment factors are used in calculating of the PNECs to consider interspecies and intraspecies variability and ranges in species sensitivity. The factor extrapolates from acute to chronic effects or laboratory data to actual field exposures (ibid.).

4.1.2 Derivation of PNECs

PNECs are usually derived by toxicological dose descriptors (acute LC_{50}/EC_{50} , or chronic NOEC/ EC_x values) and an assessment factor (AF) (EC-TGD, 2003). An AF refers to numerical adjustment that is used to extrapolate from experimentally determined dose–response relationships in order to estimate the actual substance exposure below which an adverse effect is not likely to occur.

$$PNEC = \frac{LC_{50}/EC_{50} \text{ or } NOEC/EC_x}{AF} \text{ (EC-TGD, 2003)}$$

The assessment factors are applied to extrapolate from laboratory single-species toxicity data to multi-species ecosystem effects.

Table 4.2

Assessment factor proposed for deriving Predicted No Effect Concentration (PNEC) values for saltwater (EC-TGD, 2003) with No Observed Effect Concentration (NOEC)

Data set	Assessment factor
One long-term NOEC (either fish or Daphnia)	100
Two long-term NOECs from species representing two trophic levels (fish and/or Daphnia and/or algae)	50
Long-term NOECs from at least three species (normally fish, Daphnia and algae) representing three trophic levels	10
Species sensitivity distribution (SSD) method	5-1 (to be fully justified case by case)
Field data or model ecosystems	Reviewed on a case by case basis

An assessment factor AF is used to take into account of the differences between laboratory conditions and natural conditions. The assessment factors address a number of uncertainties:

- interspecies and intraspecies variation (biological variance);
- short-term to long-term toxicity extrapolation;
- laboratory data to field impact extrapolation.

For example, if PNEC = 10 mg/l with AF of 10 and the actual concentration of the substance in aquatic environment is 2mg/L, the substance will cause unacceptable risks to aquatic environment (ChemSafetyPro, 2019).

Another method to determine a PNEC value is the use of variation in species sensitivity through statistical extrapolation. PNECs can be derived by Species Sensitivity Distribution (SSD) or fitness of all species that is logistic cumulative probability distributions of toxicity values for multiple species (Lyng, 2018). It is a distribution of chronic data based on concentrations of NOEC or LOEC.

$$PNEC = \frac{5\%SSD(50\%c.i.)}{AF} \text{ (EC-TGD 2003)}$$

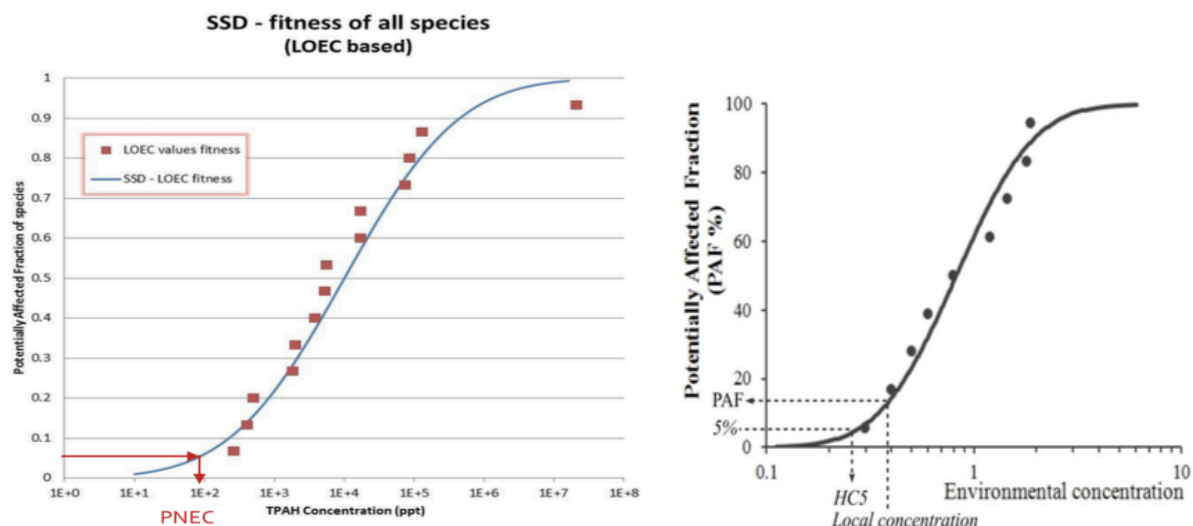


Figure 4.2: Cumulative species sensitivity distribution (SSD) with Lowest Observable Effect Concentration (LOEC) for different species (dots) used for deriving Predicted No Effect Concentration (PNEC) and calculating risk as potentially affected fraction (PAF) or the 5th percentile hazardous concentration HC_5 (Lyng, 2018; Van Leeuwen & Vermeire, 2007)

When it comes to the environmental risk assessment, the chemical concentration that is protective of most species (95%) is extrapolated from an SSD as the corresponding 5th (the fifth) percentile (HC_5) of the distribution with 95% confidence interval. HC_5 is hazardous concentration thresholds for 5% of species (Dyer, Versteeg, Belanger, Chaney, & Mayer, 2006), in other words it says a predicted hazardous concentration that affects 5% of exposed organisms or alternatively is protective of 95% of organisms. A lower HC_5 indicates higher ecological toxicity potentials.

When a large data set for different taxonomic groups is available, the PNEC can be derived by using a HC_5 value following from a statistical extrapolation method.

$$PNEC = \text{median } HC_5/AF$$

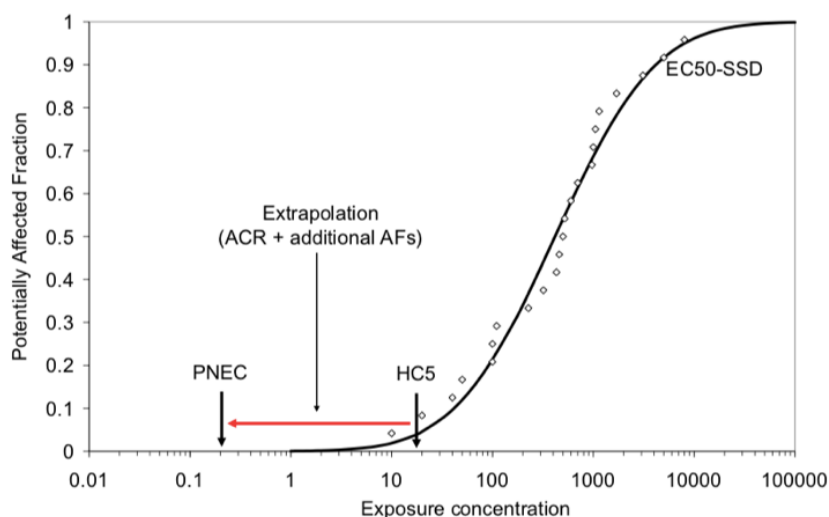


Figure 4.3: Deriving Predicted No Effect Concentration (PNEC) from hazardous threshold for 5% of species (HC₅) and an assessment factor (AF). In case of acute toxicity dose EC₅₀ - Species Sensitivity Distribution (SSD), an acute - chronic ratio (ACR) is needed (M. G. D. Smit, 2007)

Toxicological data are available for species regarding estimation of acute or chronic PNECs, normally about minimum of 15 species are chosen for being toxic tests (Lyng, 2018). The species represent three trophic levels in the water column, i.e. fish, crustaceans (as *Daphnia*) and algae, and benthos in the benthic zone and sediment, i.e. mud shrimp (*ibid.*).

4.2 Predicted Environmental Concentration in exposure assessment

In regard to exposure assessment, PEC is an indication of the expected or actual concentration of a compound in the environment. It takes into account the concentration initially present or added to the environment, its distribution, and rates of environmental degradation and removal (Férard & Blaise, 2013).

According to (EC-TGD, 2003), exposure PEC values can be achieved by modelling or using measured exposure methods. The exposure estimation includes release rates, physical and chemical properties of substance, K_{ow} coefficient, degradation rates and other fate properties.

4.3 Risks and EIF related to the PEC/PNEC ratio

Risk can be defined as the likelihood that a harmful consequence will occur as the result of an action or condition, conveys evaluations of hazards and exposure (Muralikrishna & Manickam, 2017).

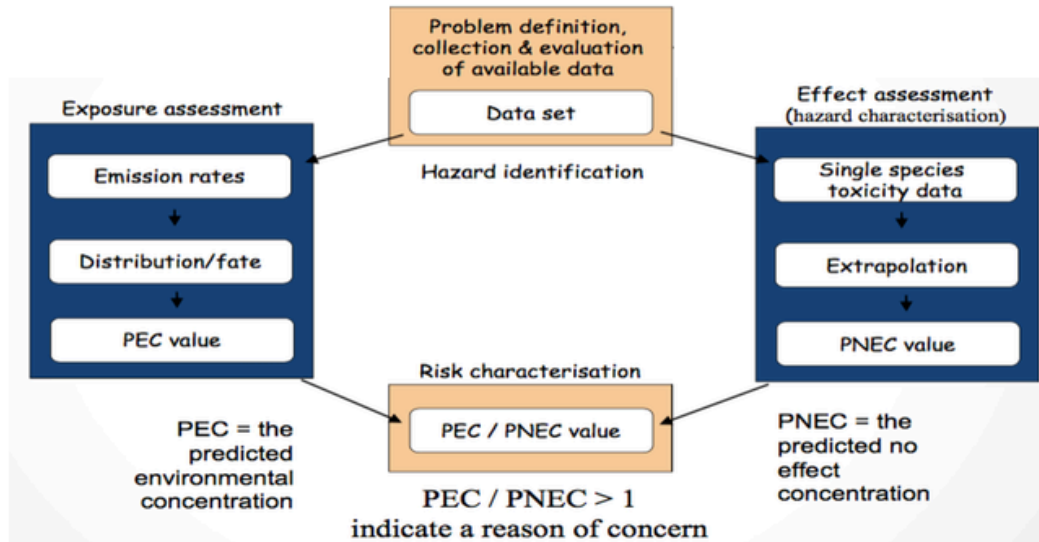


Figure 4.4: Predicted Environmental Concentration (PEC)/ Predicted No Effect Concentration (PNEC) approach in environmental risk assessment (Pampanin, 2018)

According to (EC-TGD, 2003):

$$\frac{PEC}{PNEC} \text{ whole substance} = \frac{PEC_a}{PNEC_a} + \frac{PEC_b}{PNEC_b} + \frac{PEC_c}{PNEC_c} \text{ etc.}$$

The PEC/PNEC ratio for the chemicals or compounds of the oil leakage is then used to determine the probability of impact on the exposed organisms in terms of probability of risk.

$$\text{Risk} = \int_0^{\ln \frac{PEC}{PNEC}} \left(\frac{1}{S_m \sqrt{2\pi}} \exp \frac{-(y-X_m)^2}{2 S_m^2} \right) \text{ (Rye, Reed, Durgut, & Ditlevsen, 2006)}$$

Where:

Risk = the probability that a species will be affected

X_m = a mean of the logarithmically transformed data

S_m = a standard deviation of the logarithmically transformed data

y = variable to describe the normal probability density function from 0 to $\ln \text{PEC/PNEC}$. The risk curve used for chemicals and natural compounds with: $S_m = 1.74$ and $X_m = 2.85$ (Karman, 1994; Rye et al., 2006).

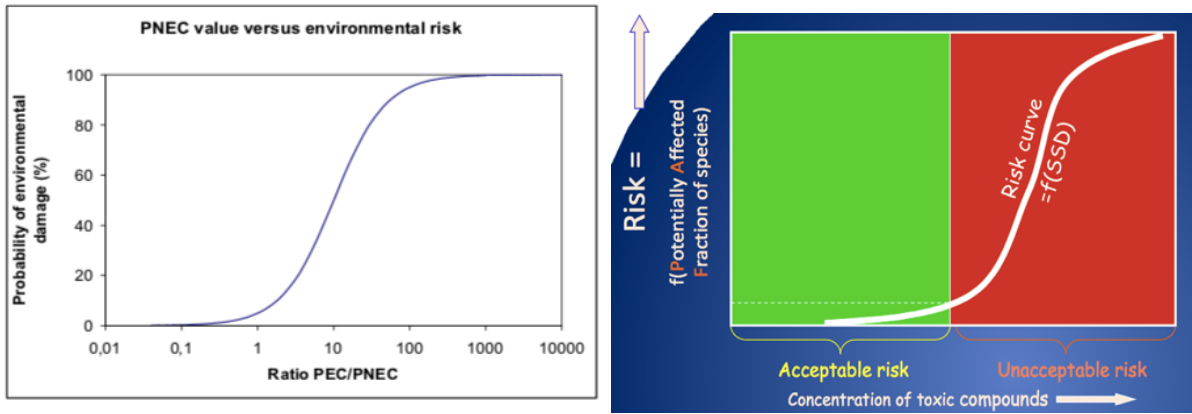


Figure 4.5: The relation between the Predicted Environmental Concentration (PEC)/ Predicted No Effect Concentration (PNEC) level and the risk level (in %) for damage on biota based on Karma et. al., 1994 (Rye et al., 2006)

At level $PEC/PNEC = 1$, this corresponds to a level of probability of damage equal to 5 %.
 When $PEC/PNEC < 1$, the probability of damage (risk) is lower than 5 %.
 When $PEC/PNEC > 1$, the risk is correspondingly higher than 5 % (Rye et al., 2006).

In environmental risk assessment, PNECs will be compared to PEC to determine if the risk of a substance is acceptable or not. If ratio $PEC/PNECs \leq 1$, the risk is acceptable, where more than 95% species will be protected (EC-TGD, 2003).

Moreover, based on the risk assessment guidelines proposed by (EC-TGD, 2003), an Environment Impact Factor (EIF) is a measure for potential environmental risk, which indicates damage on marine organisms from a discharge to sea (EC-TGD, 2003).

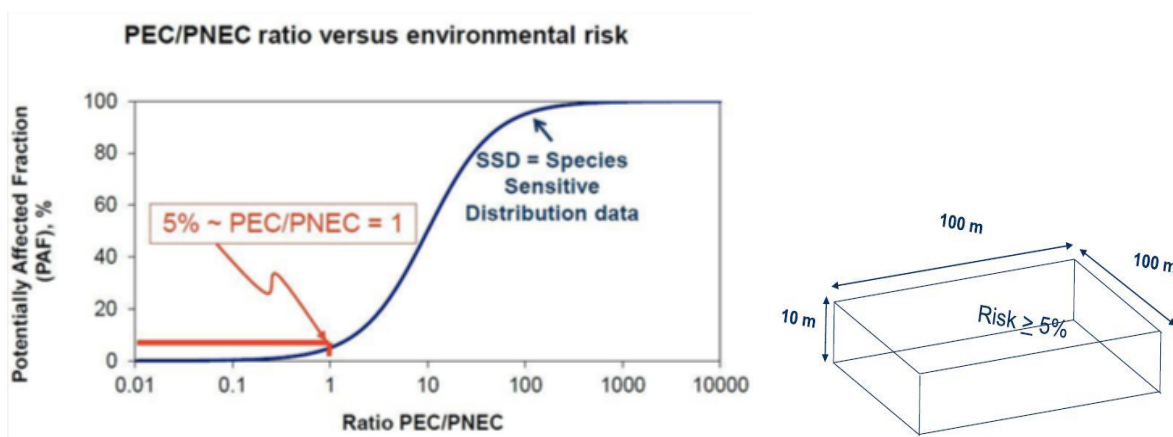


Figure 4.6: Environmental Impact Factor (EIF) related to Predicted Environmental Concentration (PEC)/ Predicted No Effect Concentration (PNEC) ratio (Lyng, 2018)

Chapter 4

The EIF equals to 1 ($EIF = 1$) is defined as a cube of 10 m x 100 m x 100 m where concentrations of substances or exposure concentrations exceeds a certain threshold value PNEC (or $PEC/PNEC > 1$), at which less than 95% of species will be protected and it means probability of damage or risk is higher than 5 % (Lyng, 2018; Rye et al., 2006).

Research Methods

A method refers to the technical steps taken to do research. The research methods as in chapter 5 and 6 are taken into account to support the description and interpretation of the research objectives and to investigate research problems.

- Literatures as data sources are more concerned with understanding the meanings and producing descriptions and interpretations (Blaikie, 2010).
- Meanwhile, quantitative methods emphasize numerical analysis of data, manipulating statistical data using computer software (Muijs, 2011).

5. Literature-based research

The literature-based research was chosen to gather and evaluate relevant information or data from previous studies. Results are obtained after a comparison of representative models under certain conditions and referring the applicable model to the database in terms of case studies in further modelling and analysis steps.

5.1 Literature-based research methodology

In order to find valuable literatures for the research subject in the vast literature ocean, it is necessary to manage the effective method to collect the documents and synthesize data.

Table 5.1

Overview of the literature research method

Literature method steps	Description	Actions
Fixing direction	- Determining the scope and nature of the research subjects	Understanding the abandoned wells, oil spill, environmental effects, regulatory requirements, modelling.
	- Knowing where the materials could be obtained	Accessing to available sources: UiS library, google scholar, oria.no, researchgate.net, websites of SINTEF, DNV GL, RPS ASA, etc.
	- Establishing literature index and materials	Classifying educational books, pictures, video, electronic data, etc. Using EndNote X9 to store the references and update citations.
Scientific reading	- Reading through literatures containing the keywords	Looking at and understanding information or data that related to oil spill model, abandoned wells, marine environment components, biological exposure and effects.
Sorting and analysing	- Identify and make judgment from the materials, - Qualitative analysis	- Picking up pertinent information, comparing, summarising and storing the words or data in to categories. - Analysing and comparing the advantages and disadvantages of models

Previous academic literatures are referenced to explain various methods that can be applied for simulations of fates and consequences of oil leakage from abandoned wells. The descriptive foundation is used to understand or explain the research problem. The process refers to fixing direction, reading through, analysing and sorting literatures in order to identify the essential attribute of information, contents and other materials for the research objectives.

The sources and authors are considered reliable in the research field and academic bases, such as the university library, researchgate.net, oria.no, websites of relevant companies (SINTEF, DNV GL), Elsevier-based publications. They cover scientific arguments and conducive research directions of using models for evaluating the environmental consequences of oil leakages. The research information and data taken from such a literature source also are comprehensive, typical and not out of date. Hereby, these literatures with authority could be believable, and be given references. The chosen literature materials therefore are pertinent and valuable for my research subject.

Based on reliable literature sources, the literature-based research method is effective in acquiring information and interpretation. Also, reflecting the benefit of the research method, the literature materials are utilized to understand the past trends, clarify existing gaps of knowledge and predict the future relevance of applying a model in simulation of oil leakage from abandoned wells.

5.2 Investigation of applicable model(s) by reviewing literatures

A leakage software system refers to different model modules, data input of initial oil properties, release information, and environmental conditions to predict future locations and state of the oil and forecast the potential effects on the environment (Fingas, 2011).

A general oil leakage modelling system includes physical fate models or oil weathering models, biological exposure models and a series of databases required by the models.

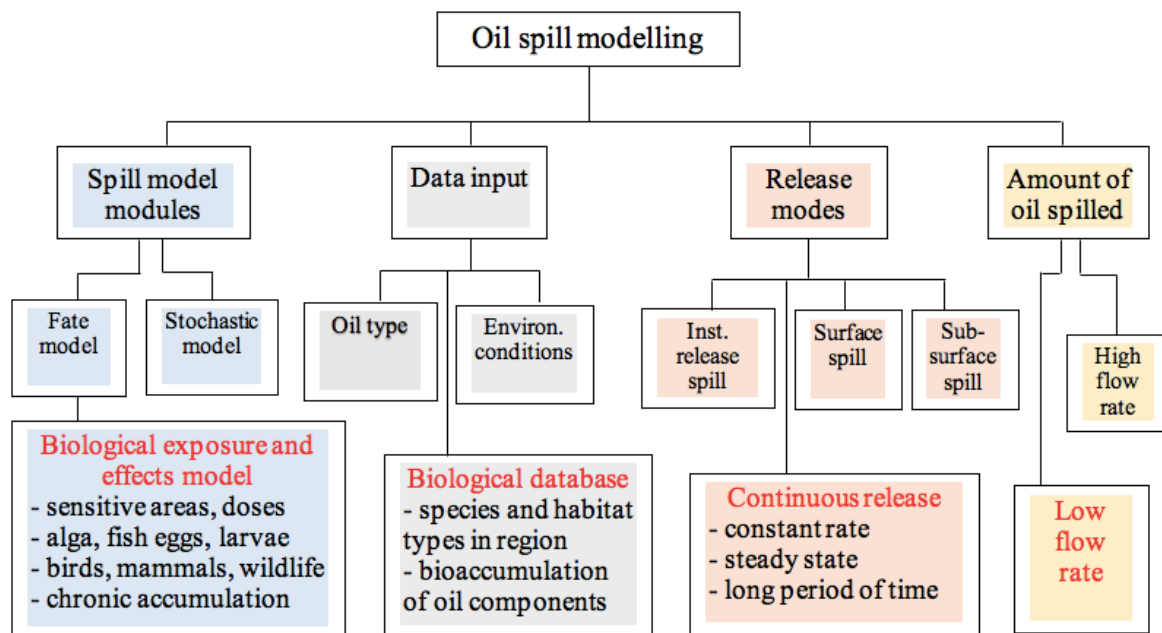


Figure 5.1: Description of oil leakage modelling system

Results of physical fate model simulations of surface spreading, advection, dispersion in water column and degradation in sediments are stored at discrete time steps in computer files and then are used as input for biological exposure models.

5.2.1 Definitions of an oil leakage modelling system

5.2.1.1 Physical fate model (trajectory and weathering model)

A physical fate component is the most typical model to describe drift trajectories or advection of oil spill and dynamic processes such as spreading, evaporation, dispersion, emulsification, biodegradation, sedimentation, etc. in the marine environment under forcing of wind, currents and waves (Fingas, 2011). The physical system includes a data-based oil weathering model on the water surface, on shorelines, in the water column, and in the sediments. It also consists of different sub-modules, such as input submodule with initial data about environment and oil spill, transport (trajectory) sub-module and fate (weathering) sub-module.

5.2.1.2 Biological exposure and effects model

A biological exposure and effects model module estimates exposure of biota to floating and subsurface oil contamination and evaluate potential acute or chronic effects on exposed organisms based on results from a physical fate module (Xiong et al., 2000). The biological data are built on threshold dose resulting populations lost, mortality and sublethal effects on production and growth (ibid.). Specifically, it can simulate the biological sensitive areas or

water volume that exposed above thresholds, and forecast exposures of fish eggs and larvae and impacts on birds, mammals, and other wildlife.

5.2.1.3 Data input

- Oil characteristics database includes data on oil type and physical-chemical properties
- Environmental database includes data on location, coastline, bathymetry, shoreline type, ecological habitat type, and temporally varying ice coverage, temperature, and salinity.
- Biological/toxicological database includes data on species and habitat type for each biogeographic region, biodegradation or bioaccumulation (French-McCay, 2004; Reed et al., 1999)

5.2.1.4 Release modes

- Instantaneous release spill refers to those spills in which oil releases with an extreme rapidity and ease or the oil spill occurs by a quick release start within a short period of time.
- Continuous release spill refers to those spills in which oil is added at the source at a relatively constant release rate in a steady state over a long period of time.
- Surface spill is when oil floats on the surface of water bodies as a discrete mass and spreads out across the surface by wind and currents to form a thin layer of oil slick.
- Subsurface spill is an oil spill that happens below the surface of the earth, the ocean (e.g. in a well or underground) (French-McCay, 2004).

5.2.1.5 Environmental (biological) exposure and effects

- Acute exposure refers to single or very limited exposure
- Acute effect (short-term effect) can be defined as adverse effect on exposed organisms that develop rapidly during short-term exposure to toxic or harmful substances. These symptoms often decline when the exposure stops.
- Chronic exposure refers to prolonged or repeated exposure
- Chronic effect (long-term effect) can be defined as adverse effect on exposed organisms with symptoms that develop slowly, due to long and continuous exposure to low concentrations of a hazardous substance. It can have long-term life-changing, adaptation or potentially fatal health implications, which may not subside even when the exposure stops (National Research Council, 2003b; Nordic Council of Ministers, 2007).

5.2.2 Model selection

There are about twenty 3D models among total fifty models (2D & 3D) used worldwide to simulate oil weathering processes and forecast the fate of oil once released. Some of them can be more comprehensive to simulate the oil weathering processes from advection, spreading to sedimentation and biodegradation at sea and along the stretch of coasts and include biological exposure and effect modules. In order to find the applicable model(s), there is a comparison of some of 3D modern models that are quite comprehensive and relevant to the study.

- SIMAP and OILMap are comprehensive 3D models developed by RPS group in the US to predict the movement and fate of spilled oil. SIMAP has both physical fate model and biological exposure and effects, while OILMap is an oil spill response and contingency planning software.
- OSCAR (Oil Spill Contingency and Response) model developed by SINTEF is a part of MEMW (Marine Environmental Modeling Workbench). Three-dimensional modeling in OSCAR provides insight into hydrocarbon transport, fate and effects during a release, and can simulate the results of different response strategies.
- SEATRACK WEB (STW) is hosted by the Swedish Meteorological and Hydrological Institute. It is very useful tool for rapid response to oil pollutions in the south–eastern part of the Baltic Sea and part of the North Sea.
- MOHID is developed by the Technical University of Lisbon and used in Portugal and Spain, it can simulate the fate and effects of both oil and gas leakage.
- DREAM (Dose related Risk and Effect Assessment Model) is developed by SINTEF and is a part of MEMW that also contains OSCAR. It has both physical fate module and biological effects module developed through laboratory studies at SINTEF and field studies in temperate and Arctic areas.
- Delft3D is developed by Deltares of The Netherlands Centre for Coastal Research. It includes an oil spill model to calculate fate of an oil patch in the aquatic environment.

In order to select an applicable model for the thesis, these models are compared on the basis of their simulation capacity in different release conditions, physical fate, biological exposure and effects as in Table 5.2.

Table 5.2

Overview of some 3D modern oil spill models. (x) means the model can simulate the process.

(-) refers to no simulation or unknown information

	SIMAP	OSCAR	OILMAP	STW	MOHID	DREAM	Delft3D
Open- source code					X		X
Instantaneous release	X	X	X	X	X	X	X
Continuous release	X	X	X	X	X	X	X
Surface spill	X	X	X	X	X	X	X
Subsurface spill	X	X	X	-	-	X	X
Advection	X	X	X	X	X	X	X
Diffusion	X	X	X	X	X	X	X
Backtracking	X	-	X	X	X	-	-
Spreading	X	X	X	X	X	X	X
Evaporation	X	X	X	X	X	X	X
Emulsification	X	X	X	X	X	X	X
Dispersion	X	X	X	X	X	X	X
Dissolution	X	X	-	X	X	X	-
Sedimentation	X	X	X	X	X	X	X
Biodegradation	X	X	-	-	-	X	X
Interaction with shoreline and coast	X	X	X	X	X	X	X
Areas/ volume exposed above threshold	X	X	-	-	X	X	X
Dose that aquatic biota exposed to	X	-	-	-	-	X	X
Exposure of algae, fish eggs or larvae	X	X	-	(*)	(***)	X	X
Contact to wildlife (birds, mammals)	X	-	-	(**)	-	-	-
Acute effects or expected mortality	X	-	-	-	-	X	-
Chronic effects	X	-	-	-	-	X	X

(Note. the information sources for this table were mainly obtained from the references and bibliography cited in this thesis report).

(*) algae observation (location, population, migration); (**) seabird tracking

(***) benthic processes, fish larvae observation (chronic accumulation, adaptation)

Table 5.2 shows that all of models chosen in comparison have comprehensive functions of physical fate in different release conditions. Among those models, the models SIMAP, DREAM and Delft3D can better simulate main processes of the biological exposure and effects. However, SIMAP is a commercial model with a close source code. Otherwise, in comparison with Delft3D and the other software, the DREAM provides more opportunity and seems to be the most reliable since its oil database is completely based on laboratory experiments (Kileso, Chubarenko, Zemlys, & Kuzmenko, 2014).

5.3 Description of DREAM – Dose related Risk and Effects Assessment Model

DREAM is initially developed for produced water discharge risk assessment. In compliance with the OSPAR guideline, this model is applied for step 2-4 to assess the potential chemical hazards, exposure to the hazardous substances and to characterize the risks of discharges to the environment.

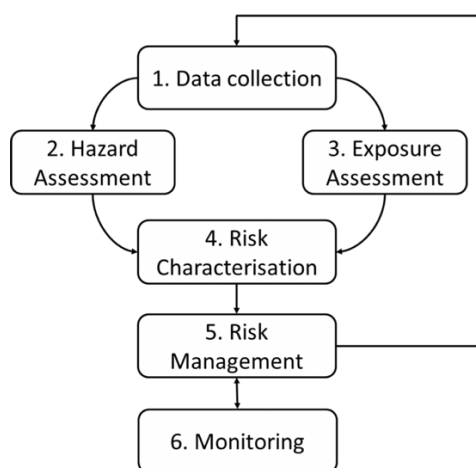


Figure 5.2: Risk-based approach (OSPAR, 2012)

DREAM helps visualizing and analyzing releases that occur over extended periods of time and in large water volumes. It calculates exposure, uptake, purification and effects on fish and zooplankton together with physical and chemical transport and fates (SINTEF, 2018). The DREAM also includes a system for calculating water volumes that are impacted by concentrations (PECs) where the sum of environmental risks caused by the concentrations exceeded 5 % probability of damage.

For each grid cell and time step, it is possible to calculate the sum of environmental risk for all compounds in the release. The total risk contribution (%) is calculated by the model for every point (grid) in space and time instant within the model domain. For a larger number of compounds, the sum of risks can be calculated from the generalized formula for the sum of

Chapter 5

probabilities as $P_{\text{sum}} = 1 - \prod [1 - P(i)]$, in which, $P(i)$ is the probability of environmental risk for compound (i) (Rye et al., 2006).

An EIF is calculated as an indicator for potential damage caused by any release or discharge, where $PEC/PNEC > 1$. DREAM is used for the EIF calculation to show the water volume where $PEC/PNEC > 1$ and the percent hydrocarbon contribution to environmental risks (Rye et al., 2006).

6. Modelling method

When it comes to the modelling of fate and effects of oil leakage from abandoned wells, it is necessary to get an understanding of availability and application of modelling methods in context. With respect to the NCS conditions, a specific scenario modeling will be carried out by using the model DREAM considering a theoretical oil leak case study at an oil field in the south Norwegian sector of the North Sea.

In order to run the DREAM, there is a need for the model's input data, such as release information, environmental data, data on physical, chemical and biological properties of the oil components including chronic PNEC values for the whole oil and for each component.

An update of database of PNEC values as the inputs for DREAM is required to implement since the model was initially developed to calculate PECs for produced water discharges into the sea and there was no focus on providing PNEC values for the oil. Thus, a model named PETROTOX and another called Target Lipid Model (TLM)-derived the 5th percentile hazardous concentration (HC₅) (or TLM-derived HC₅) estimation are used to help derive the chronic PNECs.

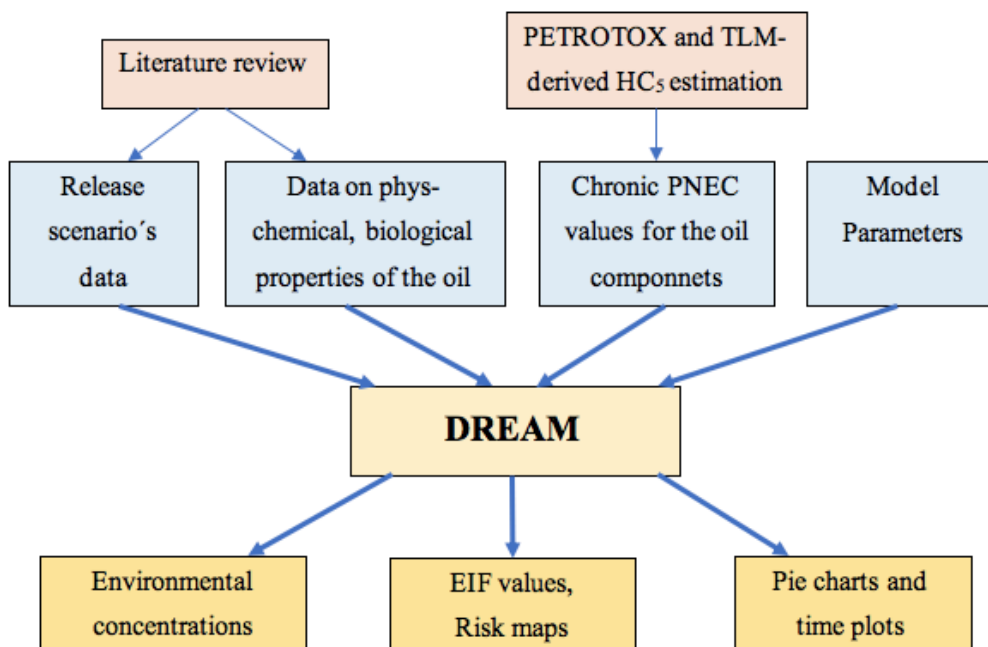


Figure 6.1: General layout of the DREAM modelling method, with PETROTOX calculation, Target Lipid Model (TLM)-derived the 5th percentile hazardous concentration (HC₅) for estimation of Predicted No Effect Concentration (PNEC), Environmental Impact Factor (EIF)

6.1 Update of the DREAM's database of chronic PNEC values

As DREAM is not generally used to compute EIF for an oil release, there has not been a focus on providing PNEC values for the oil components. Thus, in the case of modelling of oil leakage from abandoned wells, it is necessary to update the database of chronic PNEC values.

The chronic PNEC value for the whole oil is derived by chronic toxicity data NOECs, which is calculated by PETROTOX model. The chronic PNECs for each of the oil components are obtained by a TLM-derived HC₅ estimation. These values of NOECs and HC₅ will be justified by assessment factors (AFs) in order to give results of the chronic PNECs.

6.1.1 PETROTOX calculation

The PNEC value for the whole oil can be derived from predicted chronic effects (i.e. NOEC values) for available seawater species and an assessment factor (AF). The predicted NOECs are calculated by using a spreadsheet-based model PETROTOX version 3.06, which was developed by HydroQual, Inc for CONCAWE, which is a division of European Petroleum Refiners Association. This approach is used to calculate the toxicity of petroleum products to aquatic organisms, based on Target Lipid Method and Hydrocarbon Block Method. Its application has also been being mentioned by (EC-TGD, 2003) as an effective tool in derivation of PNECs.

The calculation stems from the Target Lipid Model (TLM) which is based primarily on data for aquatic test organisms using equilibrium partitioning theory (Concawe, 2011). The TLM predicts the toxicity of chemicals to aquatic organisms based on the hypothesis that target lipid is the site of toxic action within the organism and has the same physical – chemical properties in all organisms.

According to PETROTOX user's guide, the spreadsheet uses a three-phase (air, water, free product) oil solubility calculation. That goes with a database of physical and chemical properties of typical petroleum hydrocarbons to calculate the distribution of hydrocarbons based on their initial and ending boiling point ranges and fraction of weights (wt.%). The data on the oil hydrocarbon compounds in PETROTOX are treated based on the Hydrocarbon Block method, where similar components with similar properties are allocated in the same hydrocarbon blocks.

There are two modes that can be used in PETROTOX, low or high resolution, depending on the level of information available regarding the mass distribution (weight %) of the oil components. The low-resolution approach relies on the mass distribution of the two general chemical classes, aliphatic or aromatic, while the high-resolution approach relies on the mass distribution for up to 16 chemical classes.

Product Name:	test											
Date:	16/04/2019											
PROTECTION	CONCAWE											
Test Conditions:		Target Species Selection Menu										
Volume of Water (L):	0,9	Eohaustorius estuarius								INTERCEPT		
Volume of Air (L):	0,1	ID	SPECIES							(µmol / g octanol)		
Total System Volume (L):	1,0	7	Eohaustorius estuarius							41,4		
		Bioavailability Mode										
		2 Bioavailability correction with Default values: 2.0 mg/L										
		Calculate End Point										
Set Input Resolution		0	:Total Number of Hydrocarbon Blocks							Total Weight Percent:		0,00
Hydrocarbon Block	Starting Carbon Number	Ending Carbon Number	n-P (weight %)	i-P (weight %)	n-CC5 (weight %)	n-CC6 (weight %)	i-N (weight %)	Di-N (weight %)	n-Olefins (weight %)	i-Olefins (weight %)		
1												
2												
3												
4												
5												

Figure 6.2: An example of the spreadsheet-based model PETROTOX v3.06

PETROTOX can predict aquatic ecotoxicity of the crude oil substances for a given organism based on the database of each hydrocarbon block and the TLM by the target octanol (lipid)-water partition coefficient K_{ow} and the critical target lipid body burden which is species-dependent. The species need to be chosen followed by the Particulate Organic Carbon (POC) to drive the bioavailability model. Toxicity of a mixture of chemicals is driven by the sum of the toxicity of individual components. Toxicity can be assessed through LC_{50} for acute effects, and the NOEC values for chronic effects. The chronic toxicity endpoints are predicted through the use of acute to chronic ratios (ACR). In the model database, a number of acute and chronic data are available on algae, crustaceans, polychaetes and fish.

Chronic PNECs can be derived from those chronic values that providing no observed effect concentration NOEC. An assessment factor AF of 10 can then be used to justify in accordance with REACH regulation and EU technical guidance document (EC-TGD, 2003).

6.1.2 TLM-derived HC₅ estimation

Regarding PNEC values for each of the oil components, the chronic PNECs are derived by calculating the HC₅ value for each hydrocarbon component, which is a statistical extrapolation and using an AF. The derivation is based on the Target Lipid Model (TLM) (Di Toro, McGrath, & Hansen, 2000) as hydrocarbons have high solubility in lipid tissues of organisms, where toxic responses occur (Redman et al., 2014).

The TLM is a quantitative structure activity relationship model (QSAR) that is based on the chemical property of a compound (e.g. K_{ow}) and the individual sensitivity of the tested organism. In the derivation from $\log K_{ow}$ -based QSAR, a critical target lipid body burden (CTLBB) is a representative of toxicity endpoint of the challenge organisms. By the use of the CTLBB, inherent toxicity of individual hydrocarbons can be estimated (ibid.).

The calculation of TLM-derived HC₅ requires an analysis of variability in K_{ow} , critical target lipid body burden (CTLBB), ACR that is used for chronic predictions, universal target lipid slope and other variances (McGrath, Di Toro, & chemistry, 2009; McGrath, Parkerton, Di Toro, & chemistry, 2004).

$$\log HC_5 = -0.936 \log K_{ow} - \log ACR + \Delta c + \log CTLBB - k_z \sqrt{(V_{slope} \log K_{ow}^2 + V_{\log CTLBB} + V_{\log ACR})}$$

In which:

- HC₅ = hazardous concentration to 5% of species, mmol/kg
- CTLBB = mean critical target lipid body burden (μmoles/g octanol)
- ACR = mean Acute to Chronic Ratio
- k_z = 95% confidence extrapolation factor
- V_{slope} = variance in the universal target lipid slope
- $V_{\log CTLBB}$ = variance of $\log CTLBB$
- $V_{\log ACR}$ = variance in the ACR
- Δc = chemical class correction

The studies from (McGrath et al., 2009; Redman et al., 2014) show that the performance of the TLM-derived HC₅ is consistent across the range of chemicals analyzed in the study. Also, their studies contain database of TLM parameters for at least 33 to 56 individual organisms

covering 8 taxonomic groups, while REACH guidance requires 15 species covering 8 taxonomic groups. Therefore, it suggests that no additional AFs were required to establish a protective PNEC. It means an AF of 1 applied for the derivation of PNECs. Then PNEC chronic (ppb) is equal to the value of HC₅ (ppb).

Results of the PNECs calculation are presented in chapter 7.

6.2 Scenario Parameters

Scenarios for modelling are selected for an oil leak case study of an oil field at the water depth of 70 m in the southern part of the Norwegian sector in the North Sea. The oil field was discovered and initially planned to develop and operate in 1977. It had production started in 1982. A long-term strategy for the field is being developed, while wells plug and abandonment is ongoing (Norwegian Petroleum Directorate).

6.2.1 Release information

The scenario release information includes:

- Release site: at an oil field in the Norwegian North Sea. The longitude of 3°20.3806'E and latitude of 56°17.5380'N are referred to the Norwegian Petroleum Directorate's FactPages.
- Release rate: 1 L/hour
- Release duration: simulation lengths change between scenarios (e.g. 1 day, 5 days, 30 days, 60 days, 90 days)
- Release depth reference: 1 m above sea floor

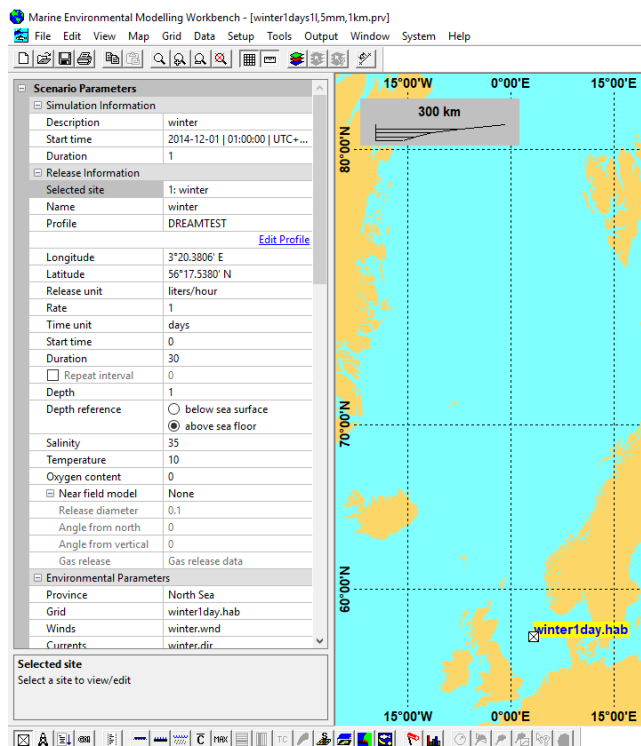


Figure 6.3: An example of scenario parameters used in DREAM

6.2.2 Oil droplet size

Based on theories of the oil droplet size distribution in the water, some different oil droplets are considered for their effects on the aquatic environment. Also, substantial differences in biodegradable rate and evaporation rate are observed between droplet sizes of 1 mm to 5 mm, according to (Tveit, 2018). Thus, the droplets of 1 mm, 3 mm and 5 mm in size are chosen to estimate risks in specific scenarios.

The rise velocity of droplets in DREAM are calculated from Stokes' law at small Reynolds numbers, with a harmonic transition to constant drag at high Reynolds numbers (Johansen, 2000).

6.2.3 Environmental data

Current and wind data required as input for DREAM modelling and calculation are collected in the regions of the Norwegian North Sea. The current and wind data are used in modelling periods including data of:

- 1 day to 90 days in winter from 01.01.2014;
- 1 day to 90 days in summer from 01.07.2014;
- 30 days from 01.12.2014.

The current data was generated by the SINMOD ocean model that is developed by SINTEF (Slagstad & McClimans, 2005) at a resolution of 1.3 km and a time step of 2 h. The model was forced with boundary conditions from a larger scale model and atmospheric data from ERA-Interim, which is a dataset showing the latest global climate reanalysis produced by the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011).

6.2.4 Oil compound groups

Similar components will act similarly and share similar properties. Thus, hydrocarbons of the oil are divided into different groups. Physical, chemical and biological properties of each group are represented by one compound or associated representative compounds of the group.

The oil compound groups with compound identification and representative compounds that are used for modelling in DREAM are presented in Table 6.1.

Table 6.1

Hydrocarbon groups used for modelling (DREAM's database and (Olsen et al., 2013))

Group	Compound identification	Representative compounds
1	C5- saturates	n-pentane, iso-pentane, cyclopentane
2	C6- saturates	n-Henxane, 2-methylpentane, 3-methylpentane, methylcyclopentane, cyclohexane
3	C7-saturates	n-Heptane, 3-methylhexane, 2,3-dimethylpentane, methylcyclohexane
4	C8-saturates	n-Octane
5	C9-saturates	n-Nonane
6	Benzene	Benzene
7	C1-benzenes	Toluene
8	C2-benzenes	Ethylbenzene: o-, m-, p-xylene
9	C3-benzenes	Propylbenzene, 1-methyl-3-ethylbenzene, 1-methyl-4-ethylbenzene, 1-methyl-2-ethylbenzene, 1,3,5-trimethylbenzene, 1,2,4-trimethylbenzene, 1,2,3-trimethylbenzene
10	C4/C5-benzenes	n-butylbenzene, 1,2,4,5-tetramethylbenzene, n-pentylbenzene
11	C10-sat (GC/FID)	C10 saturates
12	C11-C12	C11-C12 total saturates + aromates
13	C13-C14	C13-C14 total saturates + aromates
14	C15-C16	C15-C16 total saturates + aromates
15	C17-C18	C17-C18 total saturates + aromates
16	C19-C20	C19-C20 total saturates + aromates
17	C21-C25	C21-C25 total saturates + aromates
18	C26-C36	C26-C36 total saturates + aromates
19	Naphthalenes 1	C0- to C1- naphthalenes
20	Naphthalenes 2	C2- to C3-naphthalenes
21	PAH-1	C4-naphthalenes, biphenyl, acenaphthylene, acenaphthene, dibenzofurane, C0- to C1-fluorenes, C0- to C1-phenanthrenes/anthracenes, C0- to C1-dibenzothiophenes
22	PAH-2	C2- to C3- fluorenes, C2-to C4-phenanthrenes/anthracenes, dibenzofurane, fluoranthene, pyrene. C1- to C3-fluoranthenes/pyrenes, benz(a)anthracene. C0- to C4-crysenes, benzo(b,k)fluoranthene, benzo(e,a) pyrene, perylene, dibenzo(a,h,i)anthracene, benzo(g,h,i)perylene, indeno(1,2,3-c,d)pyrene
23	Phenol C0- C4	C0- to C4- phenols
24	Unresolved chromatographic materials (UCM)	UCM: C10- to C36
25	C1 – C4 saturates	C1 – C4 gases (dissolved in oil)

6.2.5 Data on physical, chemical and biological properties of the oil compound groups

Physical, chemical and biological properties of the oil compound groups used as input for DREAM are collected in Table 6.2.

Table 6.2

Physical, chemical and biological properties of hydrocarbon groups (DREAM's database)

Group	Compound identification	Fraction in oil (%)	Average boiling point (°C)	Mol weight (g/mol)	Kow	Dissolved degradation (kg/day)
1	C5- saturates	1.0504	38	66	1758	0.29
2	C6- saturates	2.2646	70	80.5	3027	0.25
3	C7-saturates	3.6520	90	99	13677	0.27
4	C8-saturates	3.7903	117	113	16520	0.27
5	C9-saturates	1.6554	147	127	57544	0.27
6	Benzene	0.3774	80	78	135	0.27
7	C1-benzenes	3.6242	110	92	537	0.46
8	C2-benzenes	0.4062	140	106	1334	0.43
9	C3-benzenes	3.8038	164	120	4159	0.43
10	C4/C5-benzenes	2.9179	187	141.5	15849	0.39
11	C10-saturates	1.5024	180	140.5	102329	0.2
12	C11-C12	2.5896	205	156.5	274157	0.2
13	C13-C14	4.3848	245	185.5	338844	0.2
14	C15-C16	2.3120	280	215.5	419759	0.2
15	C17-C18	2.4613	310	238	519996	0.2
16	C19-C20	4.8632	337	273	641210	0.4
17	C21-C25	6.3984	370	317.5	799834	0.2
18	C25+	42.2891	405	465	988553	0.2
19	Naphthalenes 1	3.3674	232	135	4266	0.63
20	Naphthalenes 2	0.1660	272	163	32063	0.49
21	PAH-1	2.6907	295	177	50234	0.46
22	PAH-2	0.0995	400	222.5	459198	0.15
23	Phenol C0- C4	0.0041	215	130	480	0.2
24	UCM (C10 – C36)	2.6707	350	215	4348.7	0.1
25	C1 – C4 saturates	0.6583	-80	37	3483	0.5

6.3 Model parameters

DREAM consists of some key model parameters, which are adjusted following release scenarios, briefly defined as follows:

Table 6.3

Key model parameters for DREAM simulations

Model parameter	Descriptions
Grid	It is a 2 or 3-dimensional mesh used to discretize space into individual cells for numerical computations. Smaller cells produce higher spatial resolution.
Habitat grid	It is a physical domain for the model operation, including rectangular grid cells. The boundary of the habitat grid is the maximum geographic area, within which water concentrations will be calculated.
Concentration grid	It is used to compute concentrations in the water column.
Time step	It is the time interval between subsequent calculations in the simulation. Smaller time steps lead to increased time resolution.
Output interval	It is frequency the concentration and risk results are written to the output data files.
Number of particles	It includes the number of liquid particles, dissolved particles and gas particles. It refers to the potential spatial resolution of the transport process since DREAM is a particle-based dilution model.

In order to set up the DREAM, the establishment of model parameters for different release scenarios is generally an iterative process. That requires to balance the spatial and temporal resolution against the practical computation time. The process of setting up DREAM for risk simulation can in other words be a trial and error process considering various testing stages of screening and iteration. The first stage with screening uses a large grid to establish the approximate extent of the polluted area where PEC/PNEC exceeds one (>1). Meanwhile, the stages with few iterations result in the actual computation of EIF and risk map.

Dimensions of the grid and time step to setting up the DREAM simulation for oil leakage scenarios are basically considered as in Table 6.4.

Table 6.4

Grid and time step considerations

Stepwise procedures	Habitat grid (km x km)	Concentration grid (cell size) (m x m x m)	Number of cells in concentration grid	Recommended time step (minutes)
Screening	10 x 10	50 x 50 x 10	200 x 200 x 10	10
Iteration 1	2 x 2	5 x 5 x 10	400 x 400 x 10	5
Iteration 2	5 x 5	20 x 20 x 10	250 x 250 x 10	1
Iteration 3	2 x 2	2 x 2 x 10	1000 x 1000 x 10	5
Iteration 4	1 x 1	5 x 5 x 10	200 x 200 x 10	1

The dimensions of the grid, the concentration grid, the number of particles and the timestep have influence the running time for the simulation. Resolutions by getting more cells, more particles and smaller time step will result in more computations being carried out by the model, which increase the time to run the simulations.

To make sure the ideal results, after running the Risk Map tool, assuring that PEC/PNEC >1 does not appear too near the boundary (Norsk Olje og Gass, 2003).

6.4 Modelling process

Under the thesis's release scenarios, the modelling process in DREAM will include flows of

- Screening simulation and iterations
- Select the applicable grid and timestep
- Computation for different oil droplet sizes over time
- Computation for seasonal variations

Results of the DREAM modelling to estimate the biological exposure and effects are presented in chapter 7.

Results and Discussion

The modelling output includes the PEC values and impacted areas as DREAM can estimate fate and concentrations of components in the discharges. Additionally, the model can show calculations of risks as EIF values.

The modelling results will be discussed in chapter 7 to evaluate the possible biological sensitive areas or seawater volume where exposure concentrations exceed a selected threshold. Also, the discussion will focus on the chronic exposures and effects of the crude oil and its hydrocarbon components. There will be a discussion over acceptable or unacceptable risks of the oil leakage to the marine organisms and some regards to potential risks are mentioned.

7. Biological exposure and effects of oil leakage from abandoned wells

Potential biological exposure and chronic effects of oil leakage from abandoned wells can be assessed by an estimation of the chronic exposure and effect values, i.e. PEC and PNEC respectively. This also includes a calculation of the risk as an EIF when it comes to environmental risk assessment.

7.1 Bioaccumulation log K_{ow}

The bioaccumulation potential of a hydrocarbon component can be assessed by its log K_{ow} . Log K_{ow} is also a variable in calculating chronic PNEC values for each of the oil components. Values of log K_{ow} calculated by K_{ow} value of each component are presented in Table 7.1.

Table 7.1

Log K_{ow} (Octanol/Water partition coefficient) calculated for each hydrocarbon component

HC group	Compound identification	Log K_{ow}	HC group	Compound identification	Log K_{ow}
1	C1 – C4 saturates	3.5	14	C13-C14	5.6
2	C5- saturates	3.2	15	C15-C16	5.7
3	C6- saturates	3.5	16	C17-C18	5.8
4	C7-saturates	4.1	17	C19-C20	5.9
5	C8-saturates	4.2	18	C21-C25	6.0
6	C9-saturates	4.7	19	C25+	6.1
7	Benzene	2.1	20	Naphthalenes 1	3.6
8	C1-benzenes	2.7	21	Naphthalenes 2	4.5
9	C2-benzenes	3.1	22	PAH-1	4.7
10	C3-benzenes	3.6	23	PAH-2	5.7
11	C4/C5-benzenes	4.2	24	Phenols C0- C4	2.7
12	C10-sat (GC/FID)	5.0	25	UCM	3.6
13	C11-C12	5.5			

Table 7.1 shows that low molecular hydrocarbons and benzenes which are volatile compounds and quite soluble in water have log K_{ow} ranging from 2.1 to 3.5. This emphasizes

previous studies by (EC-TGD, 2003) that the smaller the $\log K_{ow}$, the more soluble the substance is in water. The higher the $\log K_{ow}$, the more soluble the substance is in fatty (nonpolar) substances. Also, according to (Pampanin, 2018), substances with $\log K_{ow}$ ranging from 2 to 6 have a linear relationship between $\log K_{ow}$ and bioconcentration potentials.

7.2 Calculation results of Predicted No Effect Concentration (PNEC)

The chronic PNEC value for the crude oil is derived from predicted NOEC values for available seawater species, which are quantified by a model PETROTOX. The chronic PNECs for each of the oil components are estimated from TLM- derived HC_5 . The details of PETROTOX and TLM- derived HC_5 estimation are mentioned in chapter 6 (section 6.1). The PNECs then become a source of data input for running DREAM to produce values of PEC and EIF. These values are subsequently used to figure out the impacted seawater volume and establish risk maps for the corresponding location.

7.2.1 The chronic PNEC value for the crude oil

For the crude oil of the thesis scenario on the NCS, 25 oil hydrocarbon blocks are formed at different boiling point ranges and then used as input data for PETROTOX.

In the context of the thesis study, 16 seawater species in 4 trophic levels (fish, alga, crustacean and polychaetes) in the water column are theoretically tested in PETROTOX to obtain the outputs of chronic ecotoxicological values.

The chronic PNEC can be derived from ecotoxicity data NOEC to the assessment factor AF. The predicted chronic ecotoxicological values of NOEC calculated by PETROTOX with low resolution approach for 16 available seawater species are presented in Table 7.2.

Table 7.2

Predicted No Observed Effect Concentration (NOECs) for available seawater species calculated by PETROTOX 3.06

Species	Trophic level	Predicted chronic ecotoxicity NOEC (mg/l)
<i>Eohaustorius estuarius</i>	Crustaceans	0.20
<i>Rhepoxyinus abronius</i>	Crustaceans	0.14
<i>Mysidopsis bahia</i>	Crustaceans	0.16
<i>Chlamydomonas reinhardtii</i>	Algae	0.16
<i>Leptocheirus plumulosus</i>	Crustaceans	0.22
<i>Portunus pelagicus</i>	Crustaceans	0.29
<i>Oncorhynchus mykiss</i>	Fish	0.39
<i>Ampelisca abdita</i>	Crustaceans	0.29
<i>Paleomonetes pugio</i>	Crustaceans	0.32
<i>Cyprinodon variegatus</i>	Fish	0.90
<i>Daphnia magna</i>	Crustaceans	0.92
<i>Oithona davisae</i>	Crustaceans	1.30
<i>Nitocra spinipes</i>	Crustaceans	1.96
<i>Neanthes arenaceode</i>	Polychete	2.02
<i>Artemia salina</i>	Crustaceans	2.27
<i>Chlamydomonas angulosa</i>	Algae	6.66

Table 7.2 shows that chronic toxicity to crustaceans can range from moderate to high level when the organisms are exposed to the oil. *Rhepoxyinus abronius* is the most sensitive species among the tested species in different trophic levels in the water column. Ecotoxicological data (0.14 mg/l) from the most sensitive species *Rhepoxyinus abronius* in the water column is used for calculating of $PNEC_{\text{pelagic}}$ (or PNEC in the water column) as: $\text{chronic PNEC} = \text{NOEC}/\text{AF}$, where AF is an assessment factor designed by (EC-TGD, 2003).

Table 7.3

Chronic Predicted No Effect Concentration (PNEC) for the crude oil calculated by PETROTOX per assessment factor (AF) and No Observed Effect Concentration (NOEC)

Applied regulation	Chronic ecotoxicity data	Assessment factor	Chronic $PNEC_{\text{pelagic}}$ (ppb)
REACH	NOEC = 0,14 mg/l	10	14

According to Table 7.3, if the concentration of the substance in the marine environment is bigger than 14 ppb, the substance will likely cause unacceptable consequences to the environment. Considering simulation modelling in DREAM, the chronic PNEC_{pelagic} of 14 ppb will be a threshold value to compute impacted area or polluted volume and PECs.

7.2.2 The chronic PNECs for each of the oil components

The TLM-derived HC₅ is used to estimate HC₅ or the 5th percentile of the SSD. According to (McGrath et al., 2009; Redman et al., 2014) the TLM-derived HC₅ is calculated using:

- CTLBB = mean critical target lipid body burden = 119 (μmoles/g octanol)
- ACR = mean Acute to Chronic Ratio = 3.83 for hydrocarbons
- k_z = 95% confidence extrapolation factor = 2.3
- V_{slope} = variance in the universal target lipid slope = 2.25E-4
- V_{logCTLBB} = variance of logCTLBB = 0.105; V_{logACR} = variance in the ACR = 0.112
- Δc = chemical class correction = -0.352, -0.109 or 0.0 for di- and polyaromatic, monoaromatic or aliphatic hydrocarbons.

Table 7.4

Chronic Predicted No Effect Concentration (PNEC) for the each of oil components by the 5th percentile Hazardous Concentration (HC₅) estimation

Group	Compound identification	Chronic PNEC (ppb)	Group	Compound identification	Chronic PNEC (ppb)
1	C5- saturates	157	14	C15-C16	2.9
2	C6- saturates	109	15	C17-C18	2.62
3	C7-saturates	34.5	16	C19-C20	2.47
4	C8-saturates	33	17	C21-C25	2.34
5	C9-saturates	11.5	18	C25+	2.8
6	Benzene	1596	19	Naphthalenes 1	62
7	C1-benzenes	517	20	Naphthalenes 2	11
8	C2-benzenes	254	21	PAH-1	8.1
9	C3-benzenes	99	22	PAH-2	1.3
10	C4/C5-benzenes	33.5	23	Phenol C0- C4	811.5
11	C10-saturates	7.4	24	UCM	203
12	C11-C12	3.1	25	C1 – C4	46
13	C13-C14	3.05			

The chronic PNEC is the maximum exposure when the toxicity of hydrocarbon compounds does not occur. The smaller the chronic PNEC value of a compound poses, the lower the threshold for organism exposure becomes. It is implied in Table 7.4 that PAHs manifest the most potential toxic effects if organisms are exposed to the oils. However, the potential impact of a hydrocarbon on organisms depends on how the exposure concentration PEC of the leaky oil component compares to its PNEC. The PNEC values from Table 7.4 will be used as input data for running DREAM to estimate risks for the water column.

7.3 Simulation test with trial and error process in DREAM

In order to implement the modelling in DREAM, simulation tests are in need of trial and error process for different release scenarios. Several screening and iteration steps are executed for two simulation durations of 5 days in summer and 30 days in winter. The oil droplet sizes of 3 mm and 1 mm are used to compute EIF or risks of a continuous leakage rate of 1 L/h.

Table 7.5

Grid and timestep considerations for screening and iteration regarding simulations of 1 L/h release at the water depth of 80 m.

Test	Particle	Habitat grid (km x km)	Concentration grid (m x m x m)	Number of cells	Timestep	Output interval
5 days (from 01/07/2014)						
Test 1	30000	10 x 10	50 x 50 x 10	200 x 200 x 8	20 min	1 h
Test 2	30000	2 x 2	5 x 5 x 10	400 x 400 x 8	5min	1 h
Test 3	30000	2 x 2	5 x 5 x 10	400 x 400 x 8	1min	1 h
Test 4	30000	2 x 2	5 x 5 x 10	400 x 400 x 8	1min	5 min
Test 5	30000	1 x 1	5 x 5 x 10	200 x 200 x 8	1min	1 h
30 days (from 01/12/2014)						
Test 6	30000	10 x 10	50 x 50 x 10	200 x 200 x 8	20 min	2 h
Test 7	30000	5 x 5	20 x 20 x 10	250 x 250 x 8	5 min,	2h
Test 8	30000	5 x 5	20 x 20 x 10	250 x 250 x 8	5 min	1h
Test 9	30000	5 x 5	20 x 20 x 10	250 x 250 x 8	1 min	1h
Test 10	30000	3 x 3	10 x 10 x 10	300 x 300 x 8	5 min	1 h
Test 11	30000	2 x 2	2 x 2 x 10	1000 x 1000 x 8	15 min	1 h
Test 12	30000	1 x 1	5 x 5 x 10	200 x 200 x 8	5 min	1 h

Different seasonal scenarios are chosen in order to understand a general picture of the data availability because the actual risk computations will be executed for both seasons in winter and summer. Results from these simulation tests are showed in the following sections.

7.3.1 Simulation tests for 5-day scenarios

The 5-day simulation tests start by a screening stage with a big grid (10 km x 10 km) and time step of 20 min, then continue in 4 iterations with different model parameters of time steps and cell sizes being gradually reduced. Results of 5 tests for 5 days are collected as in Table 7.6.

Table 7.6

Results of simulation tests for 5-day scenarios of 3 mm droplets

Tests	Impacted volume (km ³)	Environmental Impact Factor (EIF)
Test 1	0	0
Test 2	1.18*10 ⁻⁴	0.0027
Test 3	1.79*10 ⁻⁴	0
Test 4	5.75*10 ⁻⁴	0.004
Test 5	1.75*10 ⁻⁴	0

Examples of testing results for 5 leakage days present as follows.

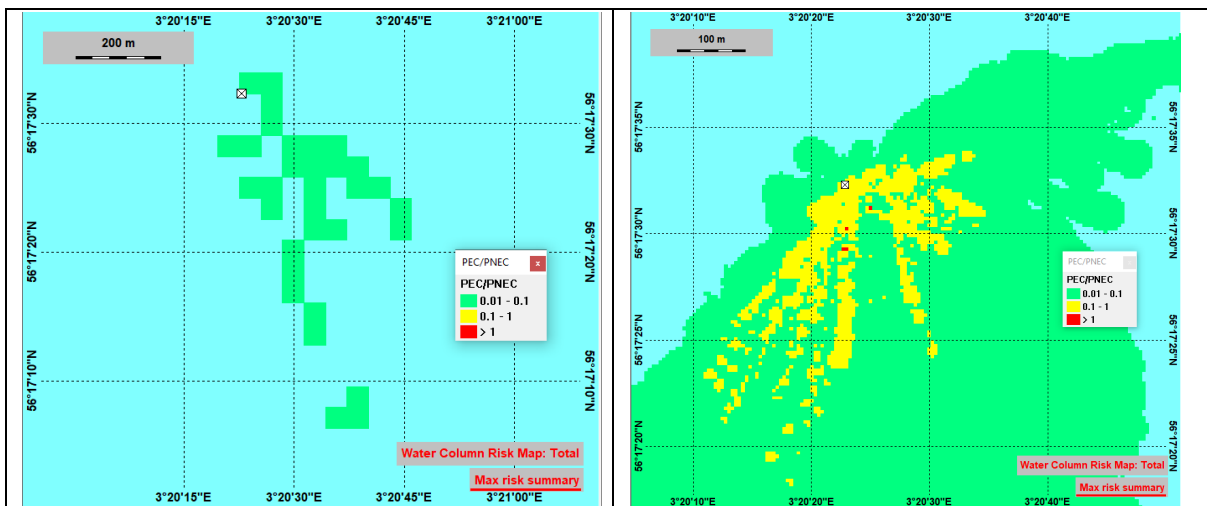


Figure 7.1: Environmental Impact Factor (EIF) = 0 by 5 leakage days
 Grid: 10x10km, concentration grid: 50x50x10
 Timestep: 5 min, output interval: 1h

Figure 7.2: Environmental Impact Factor (EIF) = 0.004 by 5 leakage days
 Grid: 2x2 km, concentration grid: 5x5x10
 Timestep: 1min, output interval: 5 min

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By reducing dimension of grids and timestep, the calculated risk contributions to the concentration field show results of maximum EIF or risk. On which, some red areas/volumes where the exposure concentration exceeds PNEC level, that is $PEC/PNEC > 1$ or probability of damage (risk) $> 5\%$, and the yellow area/volume indicates the risks between 1 to 5%.

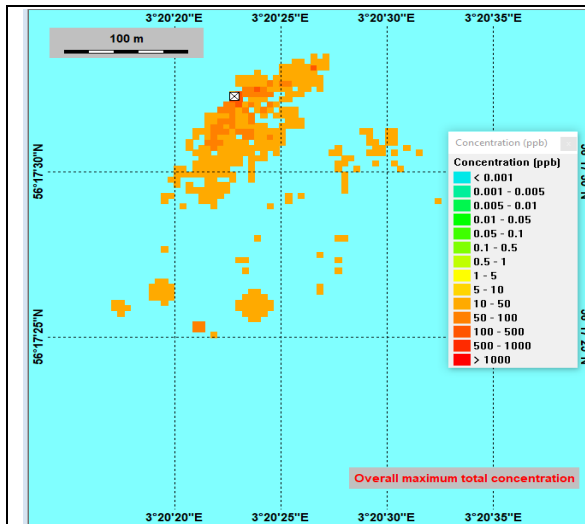


Figure 7.3: Predicted Environmental Concentrations (PECs) by 5 leakage days
Grid: 2x2km, concentration grid: 5x5x10.
Timestep: 5 min, output interval: 1h

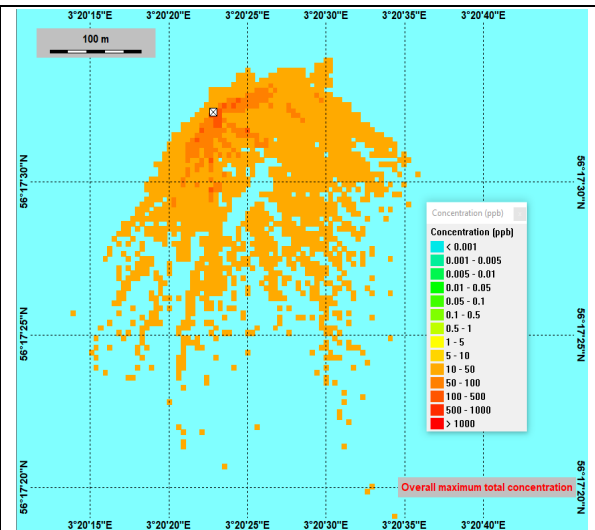


Figure 7.4: PECs by 5 leakage days
Grid: 2x2 km, concentration grid: 5x5x10.
Timestep: 1min, output interval: 5 min

From Figure 7.3 and 7.4, while considering the same dimension of the grid and same cell sizes, better result of PEC can be obtained by reducing time step and output interval.

7.3.2 Simulation tests for 30-day scenarios

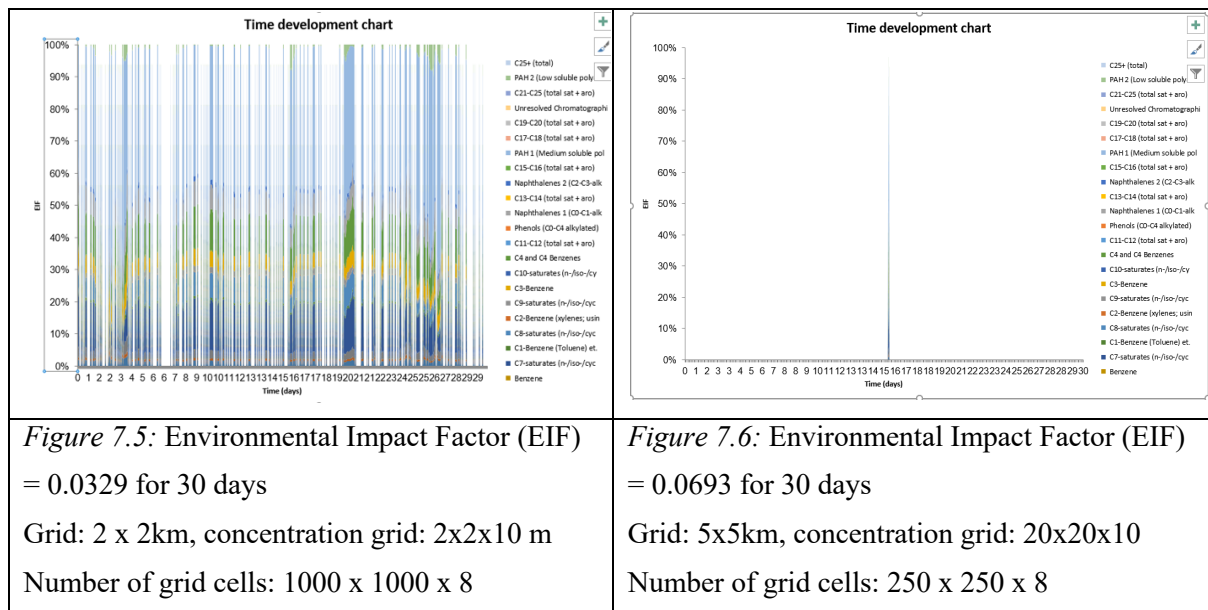
Screening with a big grid of 10 km x 10 km and number of grid cells of 200 x 200 x 8 are chosen to start testing for 30 leakage days. Iterations are undergone by reducing dimensions of grids and concentration grids, simultaneously increasing numbers of grid cells. Simulation results of 7 tests for 30-day scenarios are presented in Table 7.7.

Table 7.7

Results of simulation tests for 30-day scenarios of 1mm droplets

Tests	Impacted volume (km ³)	Environmental Impact Factor (EIF)
Test 6	0	0
Test 7	3.24*10 ⁻³	0.0693
Test 8	5.58*10 ⁻³	0.0693
Test 9	3.3*10 ⁻³	0.064
Test 10	1.59 * 10 ⁻²	0.032
Test 11	5.47*10 ⁻³	0.0329
Test 12	5.14*10 ⁻³	0.0195

Different dimensions of grids and number of grid cells provide different EIF results for 30 leakage days. Larger grids also give higher EIF values, thus distribution charts of time development EIFs are checked to assure the stability of results.



Figures 7.5 and 7.6 present the difference in distribution of time development EIFs between two different cases of dimensions of grid, cell size and number of grid cells. Technically, the EIF in DREAM is calculated on a grid, each single grid cell in which has a binary contribution to the EIF, which depends on either the concentration in each cell above the threshold PNEC (i.e. PEC/PNEC > 1) or not. Each cell of 20 m x 20 m has a volume 100 times larger than each cell of 2 m x 2 m, so each cell of the larger size will contribute 100 times more to the EIF. Due to the larger cell size on the larger grid as the Figure 7.6, the

concentration that is only large enough to give $PEC/PNEC > 1$ in one cell at one point of time contributes higher EIF than that with the smaller size. However, this indicates an uncertainty of the concentration contribution to the time development EIF regarding the larger dimension of grid and cell. By contrast, despite having lower EIF, the time development EIF on the left figure with the small grid and big number of cells distribute more often and appear for the whole point of time, which provide higher resolutions.

Consequently, a smaller habitat grid and a greater number of grid cells will increase both spatial and temporal resolutions and produce more accurate results.

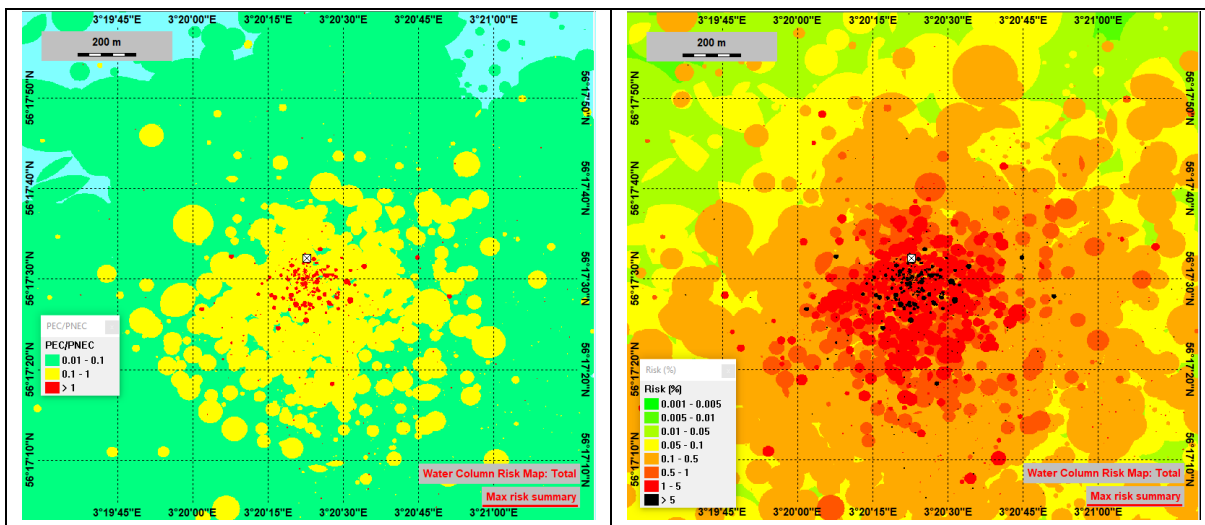


Figure 7.7: Predicted Environmental Concentration/Predicted No Effect Concentration (PEC/PNEC) and risks by 30 simulated leakage days, EIF = 0.0329, Impacted volume = $5.47 \cdot 10^{-3} \text{ km}^3$ Grid: 2 x 2 km, concentration grid: 2 x 2 x 10, number of grid cells: 1000 x 1000 x 8

Figure 7.7 displays relations between PEC/PNEC and risks by a scenario of 30 simulated leakage days, which uses a small grid of 2 km x 2 km and a great number of grid cells. The red areas on the left picture indicate exposure concentrations exceed PNEC values or $PEC/PNEC > 1$, which are related to the black areas where probability of damage or risks $> 5\%$ on the right side. The simulation results for 30 leakage days are marginally satisfactory as $PEC/PNECs > 1$ appear deep inside of the grid margin and far from the boundary.

It can be argued that in order to stabilize the modelling results, the grid and concentration grid fields should be recomputed several times. For the small leakage rate, it will be necessary to use small grids, small cell sizes, small time steps and a great number of grid cells to reduce variability.

7.4 Variation in EIF or risks by different oil droplet sizes

Calculations of EIFs or risks under the influence of oil droplet sizes (i.e. 1 mm, 3 mm and 5 mm) are executed through different release scenarios of 1 day, 5 days and 30 days from 01/01/2014. In order to see differences between 1 mm, 3 mm and 5 mm droplets, dimensions of grids and time steps keep constant for three droplet sizes with all settings and dimensions of grids and cell sizes should be as the same for all of three simulation durations.

Table 7.8

Suggested model parameter for simulation of 1mm, 3mm and 5mm droplets

Duration	Grid (km x km)	Concentration grid (m x m x m)	Timestep	Output interval
1 day	2 x 2	2 x 2 x 10	5 min	5 min
5 days	2 x 2	2 x 2 x 10	5min	5min
30 days	2x 2	2 x 2 x 10	15min	1h

Table 7.9

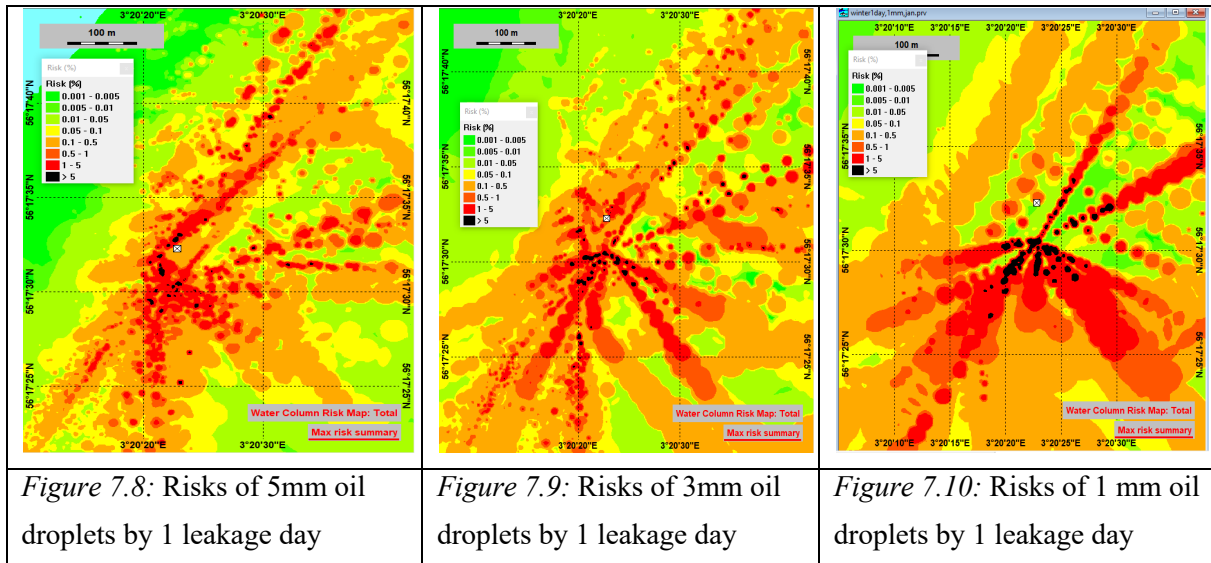
Risks and impacted areas by different oil droplet sizes of 1mm, 3mm and 5mm

Duration	Oil droplet (mm)	Impacted volume (km ³)	EIF	Distance from release site to areas with risk > 5% (for main directions)
1 day	5	3.66*10 ⁻⁴	0.0051	22 – 226 m SW; 10 – 382 m NE
	3	5.36*10 ⁻⁴	0.0083	14 – 247 SW; 10 – 340 m NE
	1	5.46*10 ⁻⁴	0.015	75 – 180 m SW; 40 – 60 m NE
5 days	5	4.33*10 ⁻³	0.0086	45 – 460m SW; 60 – 590m SE, denser areas 45-90m S
	3	4.99*10 ⁻³	0.0093	25 SW – 380 m SW; 50 – 345 m E; Denser areas around 40 – 120 m S
	1	6.26*10 ⁻³	0.0227	Denser area in 15 – 280 m SW; 0-245 m S; 0 – 150 m E; 0 – 250 m SE
30 days	5	4.03*10 ⁻³	0.0118	Scattering around to 1 km radius, dense areas in 150 m to the south
	3	4.42*10 ⁻³	0.0173	Scattering around to 1 km radius, dense areas in 150m to the south
	1	5.93* 10 ⁻³	0.0309	Dense areas within 300 m radius to the south – southeast, while some reaching out to 1 km radius

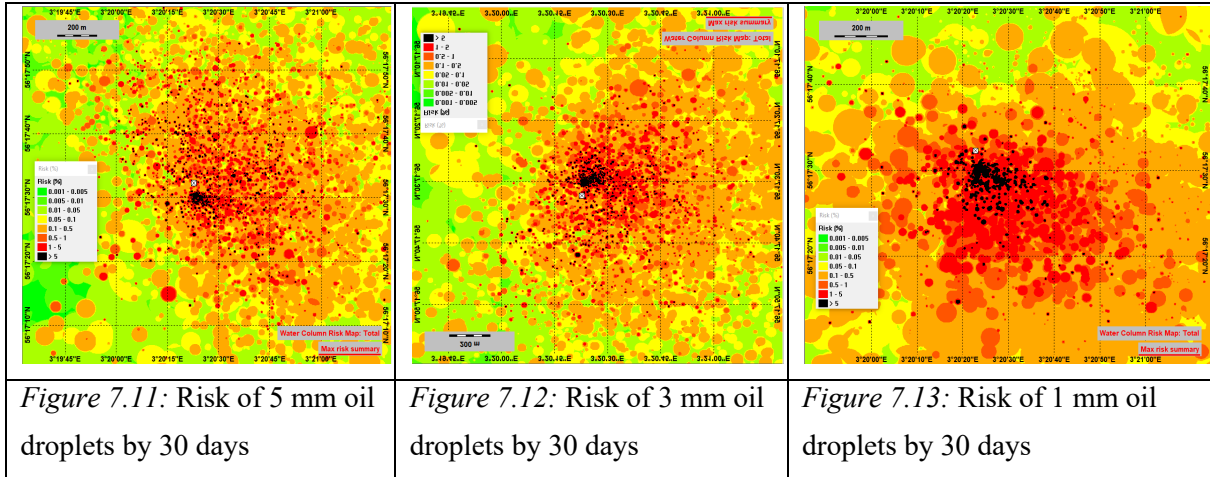
Impacted areas and EIF or risk values vary considerably between three droplet sizes. Directions of impacted areas with risk > 5% are mainly to the southwest (SW) and northeast (NE) on the first days and then around on all sides in the following days (i.e. 30 days).

7.4.1 Distribution of impacted areas by different oil droplet sizes

The total risks of 1 simulated day with the 1 mm, 3 mm and 5 mm oil droplets are compared in Figures 7.8, 7.9 and 7.10.



Occurrences of areas with risk > 5% vary between different oil droplets. For the 1 mm droplets, black areas or volumes where $PEC/PNEC > 1$ or risk > 5% appear more clearly and densely than that for the 3 mm and 5 mm droplets. Moreover, the 3 mm and 5 mm droplets scatter and disperse far away from the release site, while the 1 mm droplets move slowly within areas near the release site. Also, as per the Table 7.9 above, after 1 day, areas with risk > 5% in cases of 5 mm droplets can spread out to 226 m SW and 382 m NE in distance, while for 1 mm droplets the distances are shorter at 180 m SW and 60 m NE.



After 30 days, impacted areas with risk >5% for the 3 mm and 5 mm oil droplet disperse around the release site on all sides. Meanwhile, impacted areas of the 1 mm droplets tend to be concentrated near the release site and increased in certain areas. In general, three cases reach out to 1 km radius, including a location of denser areas located in a about 150 m distance from the site to the south - southeast for the 3 mm and 5 mm droplets and within 300 m radius mostly to the west - south – southeast for the 1 mm.

Therefore, it can be said that different droplets have different distribution patterns of the impacted areas with risks > 5%, the bigger droplets are scattered or dispersed more than the smaller droplets. The small droplets have tendency to be more concentrated to certain areas near the release site.

7.4.2 EIF development by the oil droplet sizes over time

The results of time development EIFs with different droplet sizes are presented in Table 7.10 and Figure 7. 14.

Table 7.10

Environmental Impact Factor (EIF) development by the oil droplet sizes over time

		Environmental Impact Factor (EIF) or risk		
		1 day	5 days	30 days
Oil droplet size	Duration			
	5 mm	0.0051	0.0086	0.0118
	3 mm	0.0083	0.0093	0.0173
1 mm		0.015	0.0227	0.0309

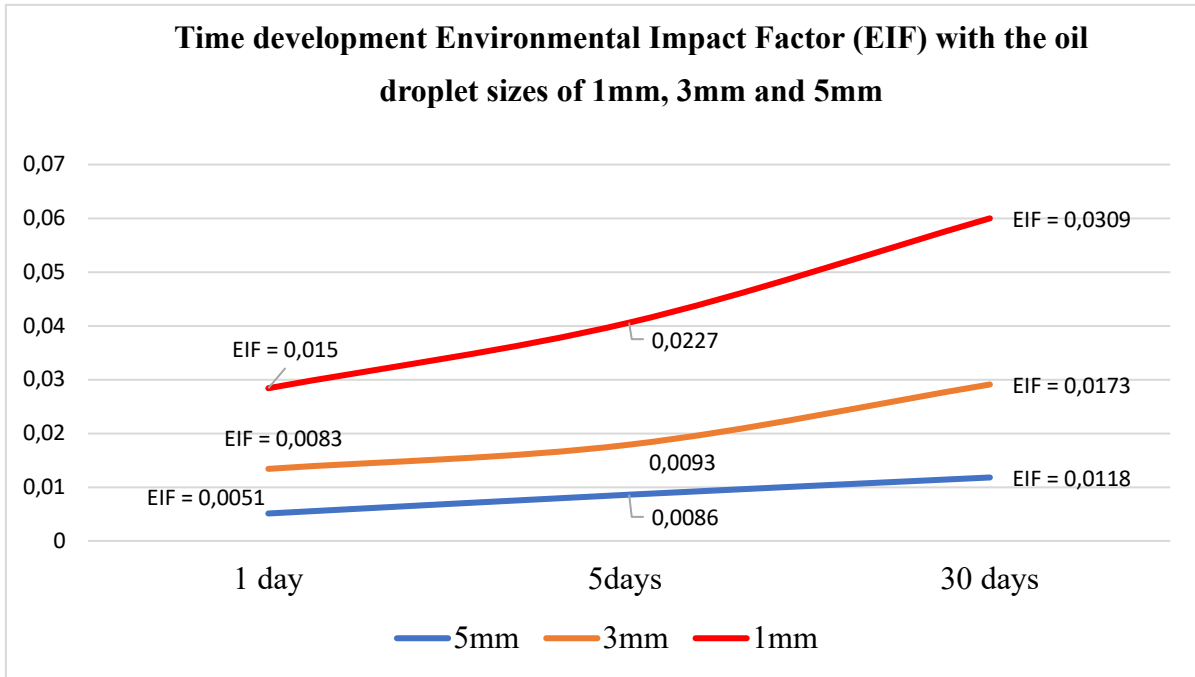


Figure 7.14: Time development Environmental Impact Factor (EIF) with oil droplet sizes

The results of EIF values are inversely proportional to the oil droplet sizes. EIFs of the smaller (i.e. 1 mm) droplets are larger than EIFs of the bigger (i.e. 3 mm and 5 mm) droplets. During 30 simulation days, the EIFs for 1 mm, 3 mm and 5 mm droplet sizes develop over time, in which the EIFs for 1 mm droplets increase significantly with time in comparison with the other sizes. Moreover, as discussed in section 7.4.1, small droplets have the tendency to be more concentrated in certain areas near the release site over time. These results are reflective of the theories that small droplets of 1 mm may be kept suspended in the water column by turbulent diffusion; and by Stokes' law they rise up to the surface more slowly than the bigger ones.

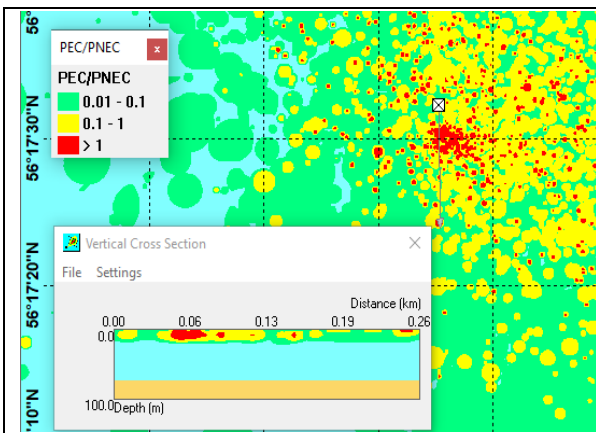


Figure 7.15: Risk for 5mm droplets floating on the surface after 30 days

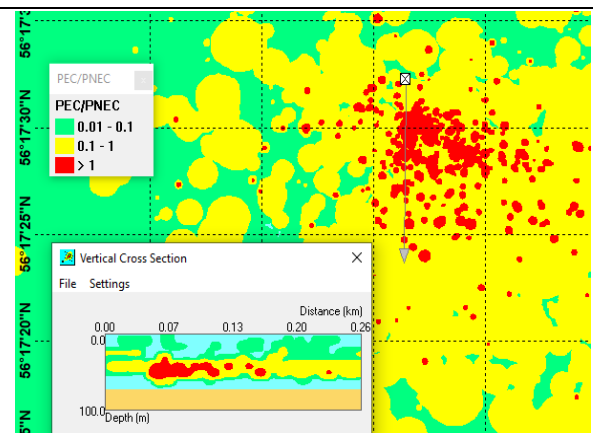


Figure 7.16: Risk for 1mm droplets being suspended in the water column after 30 days

In Figures 7.15 and 7.16, the impacted areas where PEC/PNEC > 1 for 5 mm droplets are located on the surface, while for 1mm droplets they are suspended in the water column. Hence, in comparison with the larger droplets, the smaller droplets are likely to be more easily ingested by zooplankton in the water or attached to phytoplankton, which could consequently cause chronic effects to the organisms. Thus, it can be concluded that the smaller the oil droplet sizes, the greater the impact they may have on the biological environment.

7.4.3 Hydrocarbon contributions to risks by different oil droplets

Different oil droplets respond to different manners under various environmental conditions to impact on biota and contribute to risks over time. Modelling simulations for different oil droplets will predict the contribution of hydrocarbons to EIF or risk regarding their fractions of the whole oil at the leakage times.

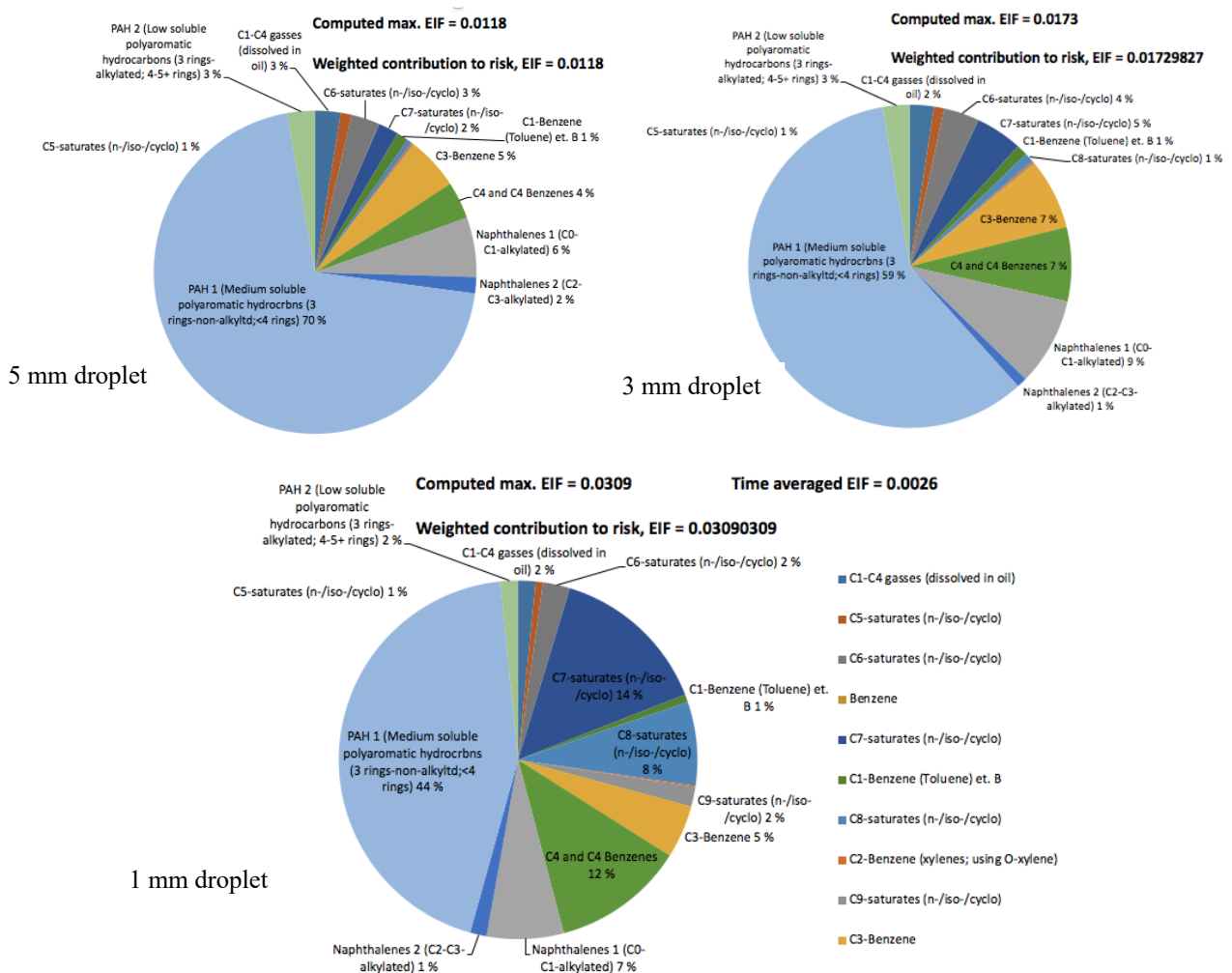


Figure 7.17: Hydrocarbon contributions to risk of 5 mm, 3 mm and 1 mm droplets by 30 days

As mentioned above, among droplet sizes, the 1 mm droplet can cause the largest effects on the environment. Figure 7.17 shows that there are slight changes in hydrocarbon contributions to risks between the 1mm, 3mm and 5 mm droplets after simulated 30-day leakages. The results indicate that PAH-1 contributes the largest fraction to the risks, emphasizing the theory from previous studies that PAHs are much less biodegradable in comparison with saturated hydrocarbons and they are considered to be the most toxic components of the crude oil.

Moreover, in Figure 7.17, the higher molecular weight hydrocarbons show no considerable contributions to the risks. According to (Neff, 2002), the higher molecular weight of hydrocarbons are less bioavailable than predicted because of limitations on their uptake rates by organisms, their lower solubility in tissue lipids, and rapid metabolism of higher molecular weight in some marine animals. Besides that, in regard to the relation between bioconcentration potentials and $\log K_{ow}$ values, chemicals with high $\log K_{ow}$ values (i.e, from 4.5 to 6.0) are of greater concern because they may have the potential to bioconcentrate in living organisms, otherwise increasing $\log K_{ow}$ from 6.0 and above leads to reduce the bioconcentration potential (Dimitrov et al., 2012). These theoretical views can be exemplified through the results in Table 7.1, in which the compounds of C9-C10, cycloparaffins and PAH-1 have their $\log K_{ow}$ bigger than 4.7 and less than 6.0, meaning these compounds have more potential of bioconcentration in organisms. Meanwhile, the high molecular weight hydrocarbons and PAH-2 have $\log K_{ow}$ values reaching up to 6.0 or nearly 6.0, so they may be far less soluble in tissue lipids of organisms and have their lower bioconcentration in the organisms. This leads them to have smaller contributions to risks than the low molecular weight compounds.

When it comes to effects of the oil diameter sizes, Figure 7.17 also points out that in addition to main PAH-1s, the contributions of other toxic components such as naphthalene 1, C4 benzenes and C7-C9 saturates of the small (i.e. 1 mm) droplets increase more largely than that of the larger (i.e. 3 mm and 5 mm) droplets. This can be more clarified by Figures 7.18 and 7.19 below. During the first leakage day, hydrocarbon fractions of the larger (3 mm) droplets vary strongly, while hydrocarbons of the smaller droplets keep on almost the same levels to contribute to risks.

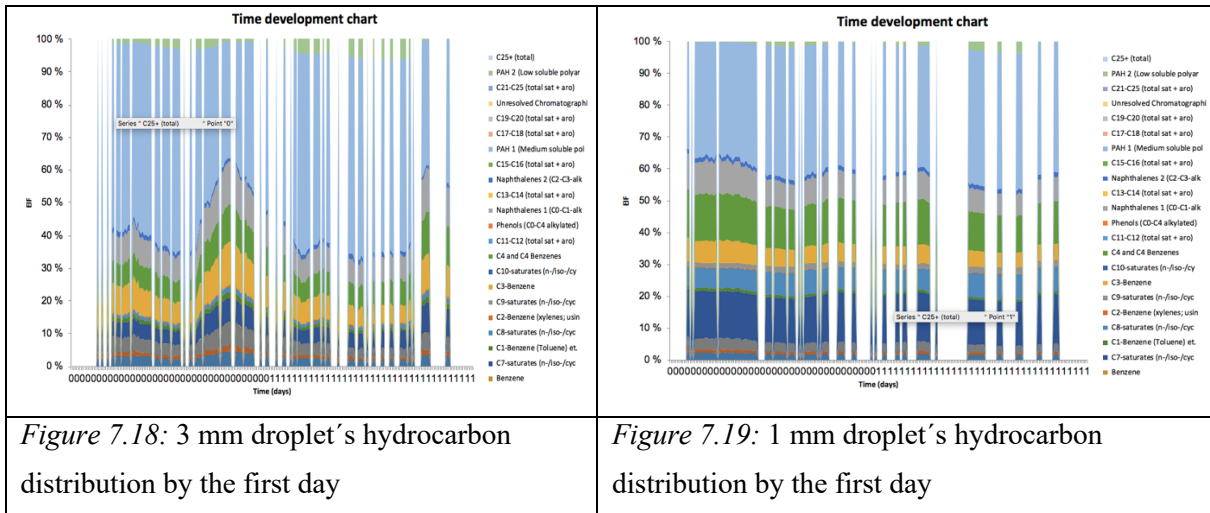


Figure 7.18: 3 mm droplet’s hydrocarbon distribution by the first day

Figure 7.19: 1 mm droplet’s hydrocarbon distribution by the first day

These results can prove the theory that the evaporation rate increases with increasing droplet size, since the bigger ones can rise quicker in the water column or on the surface where the evaporation and oxidation happen, while the smaller ones are better at dissolving in the water due to their large surface-area-to-volume ratios. Thereby, monocyclic aromatic hydrocarbons (e.g. benzene, toluene, ethylbenzene) or the low molecular weight hydrocarbons (C1 to C9) in the larger droplets will be lost rapidly by evaporation under their vapor pressure and oxidation with oxygen in the water. Then, they occupy lower fractions in the larger droplets than do in smaller droplets as they show in the simulations of different day leakages.

Therefore, it could be said that besides PAH-1s, toxic hydrocarbon components of naphthalene 1, C4 benzenes and C7 – C9 saturates should be of concern when it comes to effects of the oils.

7.5 EIFs or risks by seasonal variations

As described in chapter 3 (section 3.4), variations in the water temperatures or seasonal thermocline month on month are observed over the depth of 70 m up to the surface. Temperatures or thermoclines of the winter months significantly distinguish from that of the summer months.

Scenarios for risks by seasonal variations consider the oil droplet size of 1 mm and 5mm droplets and simulation length of 5 days and 30 days with the winter from 01/01/2014 and the summer from 01/07/2014.

Table 7.11

Environmental Impact Factors (EIFs) in summer and in winter

Droplets	Summer		Winter	
	5 days	30 days	5 days	30 days
5 mm	0.0074	0.0085	0.0086	0.0118
1 mm	0.023	0.0336	0.0227	0.0309

The EIF results vary between two droplets during two seasons, EIFs for the 1 mm droplets seem to be slightly higher in summer than in winter; in contrast, EIFs for the larger (5 mm) droplets show lower in summer than in winter.

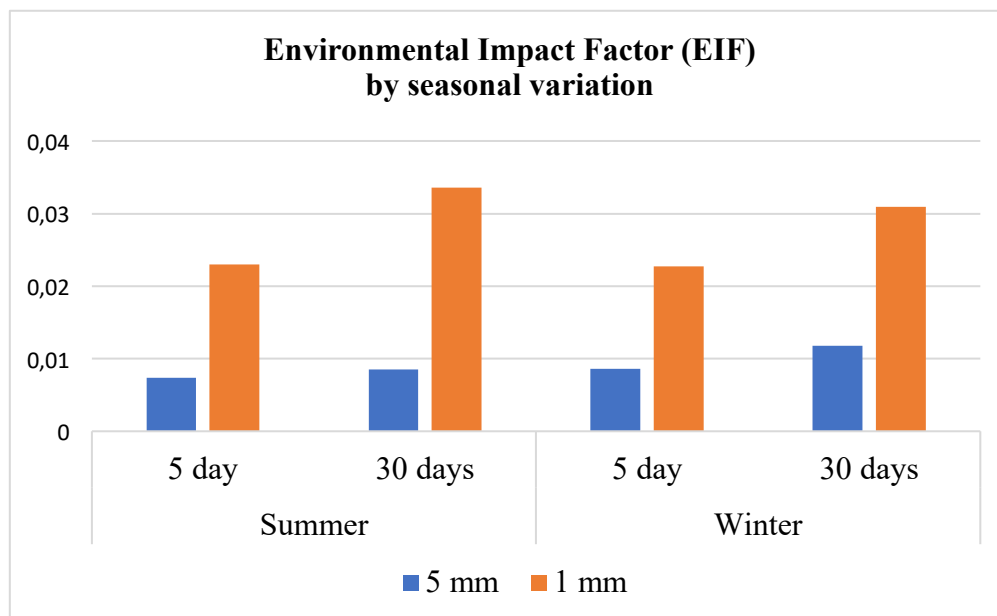


Figure 7.20: Environmental Impact Factors (EIFs) in summer and in winter

With respect to the oil behaviors in summer and in winter, previous studies including (Goosse, 2015) mentioned stronger wind and current leading to more water mixing happening during winter. That can help the suspended smaller (1 mm) oils become more diluted or dispersed in the water column. In summer, in contrast, the thermocline is observed to separate the vertical water medium into two water layers, the shallow warmer and more mixed upper layer and the deep cooler and less mixed lower layer. According to (Delvigne & Sweeney, 1988) and (Wolfe, 2013), small droplets in summer would be kept suspended in the water column and trapped under the thermocline, where greater oil-water contacts and water-in-oil emulsion could occur resulting in more biological exposure to the oils. Also, in the warmer water column, a larger number of species (e.g. phytoplankton, herring, blue whiting, cod)

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extend their habitats, growing and spawning more rapidly. These views explain simulation results with higher EIFs or risks for smaller droplets in summer than in winter.

On the other hand, the larger (5 mm) droplets can move up on the surface faster than smaller (1mm) droplets. The rising process can then be speeded up by currents at different water depths. During the summer, according to the (National Research Council, 2003b; Perry, 1984), higher evaporation and oxidation rates can likely make n-alkanes, monocyclic hydrocarbons, benzenes and other volatile toxic hydrocarbons become more rapidly lost to reduce toxicity of the oils. Thus, they contribute fewer fractions to risks in summer than in winter, as illustrated in Figure 7.21. As a result, EIFs or risks of the larger droplets could be seen lower in summer than in winter.

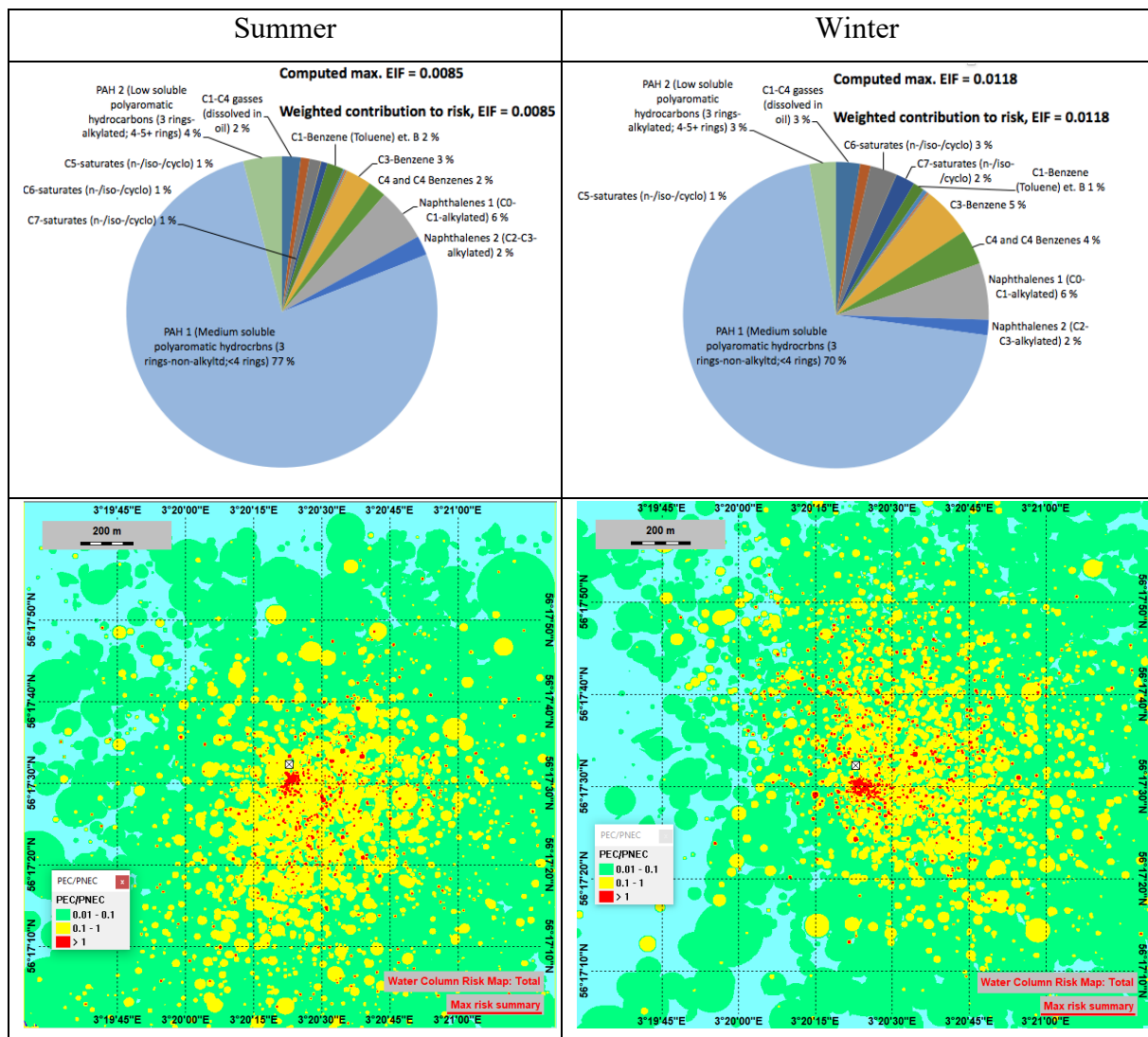


Figure 7.21: Risks and hydrocarbon contributions to risks by 5 mm droplets in summer and in winter

In essence, as calculations of EIF in DREAM are determined by the local current and wind, it can be argued that EIFs or risks of the oil leakage could be likely influenced by processes of dilution, dispersion, evaporation and oxidation under variation of the ocean current and wind regimes in the water column and on the surface.

7.6 Acceptable risks

Considering long-term effects or chronic risks of the oil leakage with a constant release rate in a steady state over a long period, a scenario is set up for 1 L/hour leakage of the 1 mm droplets during 1-day, 5-day, 30-day and 60-day and 90-day simulations starting from 01/01/2014. The grids and other model parameters in Table 7.8 are used for these scenarios, in which parameters for 60 day and 90-day simulations keep the same as those for the 30-day simulations.

Table 7.12

Results of 1-day, 5-day, 30-day and 60-day and 90-day simulations

	Simulation duration				
	1 day	5 days	30 days	60 days	90 days
Impacted volume (km³)	5.46*10 ⁻⁴	6.26*10 ⁻³	5.93 * 10 ⁻³	9.18*10 ⁻³	1.73*10 ⁻²
EIF (risk)	0.015	0.0227	0.0309	0.0336	0.0329
Distance from release site to areas with risk >5%	75 – 180 m SW; 40 – 60 m NE	Dense areas in distances 15 – 280 m SW; 0-245 m S; 0 – 150 m E; 0 – 250 m SE	Dense areas within 300 m radius mostly to the west - south – southeast, while some reaching out to 1 km radius	Dense areas within 300 m radius mostly to the west-south – southeast, while some reaching out to 1 km radius	Dense areas within 300 m radius on all sides and out to 1 km radius

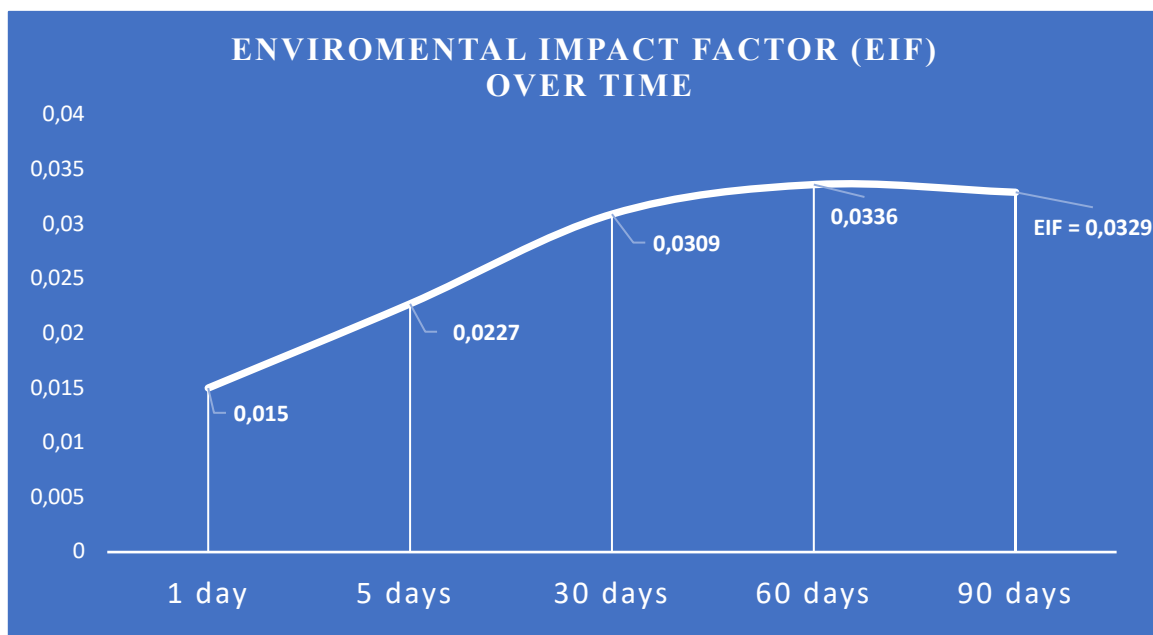


Figure 7.22: Distribution of Environmental Impact Factor (EIF) over time

The simulation results show that impacted areas or pollution volumes are continuously enlarging overtime. Simultaneously, during the first 30 days, the EIFs increase considerably from 0.015 to 0.0309, while a period of the next 30 days to 90 days show no significant variations in EIFs as they vary between 0.0309 and 0.0329. As EIF calculated by the water volume of 100 m x 100 m x 10 m where $PEC/PNEC > 1$, increasing in impacted areas and reducing in the exposure concentration could imply the influence of physical spreading or dispersion of oil leakage and chemical or biological alterations of the oil components by time.

The simulation results also indicate that no matter how long the simulation durations are, distances from the release site to the areas with risk $> 5\%$ are kept within 1 km radius from the release site. Also, the impacted areas become denser and more compacted over time in a certain cluster of impacted areas at a location nearby the release site as in Figure 7.23. Given that EIF calculations are based on the local wind and current for a given period, the results of 30-day, 60 day to 90- day simulations produce EIFs that reach and stay the same at a particular level. Consequently, EIFs show more stability over longer periods.

Furthermore, previous studies mentioned the formation of a diverse community within several meters or at some distances from areas of active seepages. Alteration on populations and adaptation of marine organisms over generations were also observed near the sources of natural seep, according to the (National Research Council, 2002) and (Heiko Sahling et al., 2016). It could be argued that long-term exposure to the continuous low-rate oil leakage,

chronic or long-term effects on organisms would potentially occur at some point and a steady state effect is likely to remain over a long period.

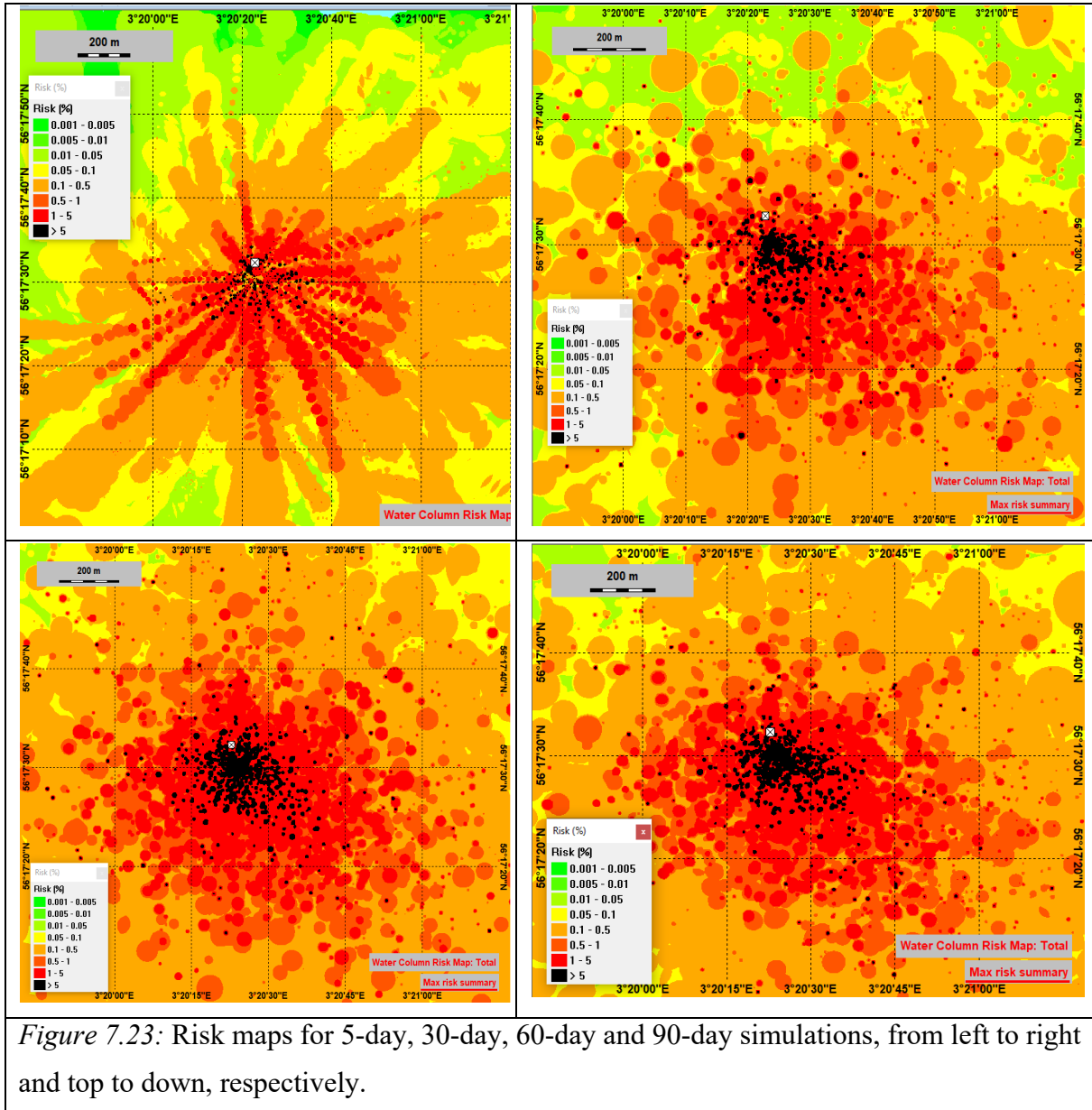


Figure 7.23: Risk maps for 5-day, 30-day, 60-day and 90-day simulations, from left to right and top to down, respectively.

With respect to the “zero discharges” goal, it would be necessary to evaluate whether the chronic risks of long-term effects on marine organisms are acceptable or not, and in what manner such potential risks of oil leakage from abandoned wells can be dealt with.

As per Figure 7.23, the black areas increasing from 5 days to 90 days surrounding the release site signify $PEC/PNECs > 1$, or probability of damage or risk $> 5\%$ that indicate some unacceptable risks, which then need further mitigation measures. Thus, the environmental consequences in terms of chronic biological exposure and effects by continuous low-rate oil

leakage from abandoned wells must somehow be considered when it comes to “zero harmful discharges”.

7.7 Regards to potential risks of chronic exposure and effects of oil leakage from abandoned wells

A lesson taken from the Zero Discharge Program for produced water discharge is that estimation of risks by EIFs can help to determine the source of potential environmental damage and quantify the benefit of any action taken to reduce risk (Johnsen, Frost, Hjelsvold, & Utvik, 2000). Available technologies for risk reduction and removal or replacement of chemicals are amongst solutions that the operators on the NCS are focusing on in order to improve the EIF for single platform (ibid.). When it comes to oil leakages, a consideration could hence take into account of identification of hydrocarbon contributions to risks through computation of EIFs as having done in the thesis. Based on the toxicological hazards, toxic hydrocarbon components of the crude oil, for example PAH-1s, naphthalene 1 or C4 benzenes, etc., should be in essence tested and categorized with reference to the 4 color-coded groups of black, red, yellow and green being currently applied for offshore chemicals in Norway. Unlike produced water composition, hydrocarbon components of the crude oil are determined by the oil leaking from the reservoir. Removal or replacement of chemicals could be not an option for the oil leakage. Instead, estimation of EIF and hydrocarbon contributions to risks might be used to identify potentially harmful leakages and monitor environmental risks. Besides that, prediction of polluted locations and estimation of impacted areas from the oil leakage sites could be supportive for mitigation measures on a cost-benefit basis.

Moreover, all of the operators on the NCS have effectively used the EIF to quantify and document the environmental risks from produced water discharges and report their improvement progress to the regulators (D. Smit et al., 2011). It should therefore be argued that implementation of the EIF tool for oil leakages from abandoned wells can likely facilitate the risk management and regulation for P&A activities.

Additionally, according to NORSOK Standard D-010, there is no monitoring required once the well is permanently abandoned. Therefore, in addition to the environmental risk assessment in the abandonment area, the environmental monitoring for the water column might be essentially carried out regarding permanent abandoned wells.

Conclusion

The conclusion presents a summary of the insights of the research to provide with achievement and knowledge that the research has advanced. Recommendations for future work on the topic are also included to suggest a beneficial solution to the issues of environmental fate and effects when it comes to modelling of oil leakage from abandoned wells.

8. Conclusions and recommendations

8.1 Conclusions

With the aims of providing an approach to modelling biological exposure and effects of oil leakages from abandoned wells, the thesis has shown that estimation of biological exposure and chronic effects by continuous low-rate oil leakages can be achieved through simulation modelling.

By a modelling study of specific scenarios at an oil field on the NCS, it is possible to conclude that:

- With respect to small leakage rate, simulations in a biological exposure and effect model should use small grids, small cell sizes, small time steps and a great number of grid cells to obtain the stability.
- Impacted areas or pollution volume and chronic risks of oil leakage can be predicted and estimated by the EIF, considering chronic PNEC or threshold for each of the oil components.
- Impacted areas with risk > 5% become denser and more compacted over time in a certain location of a few hundred meters from the release site.
- EIFs or risks develop by time and stay the same at a particular level. EIFs become more stable over longer periods, resulting in potential chronic exposure and effects on organisms with a steady state effect.
- Appearance of unacceptable risks where PEC/PNECs > 1, or risk > 5% surrounding the release site indicates a need of mitigation measures and more considerations regarding a “zero discharges” goal.
- Physical, chemical and biological characteristics of hydrocarbon groups, sizes of oil droplet, along with the ocean temperature, wind and current regimes will be parts of influence factors on fate and effects of the oil leakage from abandoned wells.
- Dilution, dispersion, evaporation, oxidation and biodegradation are parts of the contributing processes to fate and effects of the oil leakage.
- Small oil droplets (i.e. 1 mm) are more concentrated to certain areas near the release site, while the bigger droplets (i.e. 3 mm and 5 mm) are more dispersed.

- Smaller droplets being suspended in the water column can have the greater impact on the marine biological environment than the bigger droplets floating on the surface.
- Environmental risks vary between different oil droplets in summer and in winter. The smaller droplets have higher risks in summer than in winter, while the larger droplets cause lower risks in summer.
- Among hydrocarbon compounds, PAH-1 contributes the largest fraction to the risks, with approximately 44% to 70%. Considering bioconcentration potentials and $\log K_{ow}$ values, the higher molecular weight hydrocarbons show no considerable contributions to the risks. Besides PAH-1s, toxic hydrocarbon components of naphthalene 1, C4 benzenes and C7 – C9 saturates should be of concern.

8.2 Recommendations for future works

8.2.1 Simulation of the sediment

Risk calculations for the water column require input values of $PNEC_{pelagic}$, while the sediment risk assessment requires data of $PNEC_{sediment}$. In order to obtain values in the sediments, there will be a need for a large database of stressors, such as change in particle sizes, oxygen depletion, burial and toxicity. Moreover, the oil includes mainly organic hydrocarbons, without concerns of materials of sediment deposits, such as heavy metals, inorganic salts and particles. Also, by leaking at very low rate from abandoned wells, the oils with droplet size of 1 mm are not too small to be trapped in the sediment. Thus, it was considered not to estimate the sediment risks for oils in the thesis. However, the work estimating risks for the sediment by leakages from abandoned wells would be recommended for future studies.

8.2.2 Simulation of the surface

The surface signature of a leak could also be important to consider as the slick oils and tar balls floating on the surface are potentially toxic to seabirds and marine mammals (National Research Council, 2003a). The fate and effects of oils on the surface depend on the oil droplet size, type of oil and water depth at the location.

8.2.3 Simulation for deep-water fields

Simulations in the thesis are conducted with scenarios of 80 m water depth as the oil field is located in the area of about 70 m water depth. As discussed in the thesis, the ocean currents at different depths and the oil-water contacts are parts of the influence factors on fate and effects of the oil leakage. According to (Norwegian Petroleum, 2019), about 82% of the drilled wells are located at the North Sea, where has the water depth of average 90 m and maximum 700 m. Thus, simulations for the deep-water scenarios are highly recommended for future works.

8.2.4 Study of local biological conditions

The EIF is a crude approach that tries to reduce a complex environmental situation down to a single number for management purposes. However, a leakage in a spawning area during the spawning period might be more sensitive than elsewhere and become a problem of sustainable management. Thus, a more detailed study would take into account of local biological conditions.

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