

**RISK-BASED APPROACH TO THE MANAGEMENT OF
PRODUCED WATER IN OIL AND GAS INDUSTRIES:
ITS POLLUTION PREVENTION AND MITIGATION**

Almat Kaby1, Bachelor of Natural Science in Chemistry

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**School of Engineering and Digital Sciences
Department of Chemical and Materials Engineering
Nazarbayev University**

53 Kabanbay Batyr Avenue,
Nur-Sultan, Kazakhstan, 010000

Supervisor: Dr. Ming Yang
Co-Supervisor: Dr. Vassilis J. Inglezakis

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Abstract

Produced water is a waste of significant concern due to its high volume being produced every day and complex chemical composition. In order to meet environmental regulations and standards, different techniques can be used to treat produced water. This work first summarizes produced water composition, its related environmental impact, regulations, and standards, as well as a possible combination of different treatment techniques. The work aims to develop a generic framework for a risk-based approach to produced water management. The proposed methodology considers the integration of environmental, technical, and economic risks in the decision-making process for produced water management. Environmental risk assessment is conducted by Dose-related Risk and Effects Assessment Model (DREAM), Failure Mode and Effects Analysis (FMEA) is used to estimate technical risk, and cost-benefit analysis is performed to calculate economic risk. To integrate all the risk values, acceptable risk levels are set and compared to the calculated risk values. Experts assign weighting factors by using pairwise comparison. The sum of the multiplied weighting factors to the ratio of calculated-acceptable risk values gives the final integrated risk. This framework can help to examine and select the most suitable treatment or reuse technique or identify potential areas for improvement in a specific site. The estimated risk can be used to justify the selection process. A case study on the produced water treatment in Thunder Horse Oil Field is presented to demonstrate the application of the proposed framework.

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List of Abbreviations & Symbols

BAF	Biological aerated filters
BTEX	Benzene, toluene, ethylbenzene, and xylenes
CFU	Compact flotation unit
COD	Chemical oxygen demand
DAP	Dissolved air precipitation
DREAM	Dose-related Risk and Effect Assessment model
EIF	Environmental Impact Factor
FMEA	Failure Mode and Effects Analysis
HYCOM	Global Hybrid Coordinate Ocean Model
LogP _{ow}	Bioaccumulation tendency
NOEC	No observed effect concentration
NORM	Naturally occurring radioactive materials
PAH	Polycyclic aromatic hydrocarbons
PEC	Predicted Environmental Concentration
PNEC	Predicted no-effects concentration
PPM	Parts per million
RPN	Risk priority number
SRT	Solids retention time
SSD	Species Sensitivity Distribution
TPH	Total petroleum hydrocarbon
TSS	Total suspended solids

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Chapter 1 - Introduction

1.1 Background of the research problem

Produced water is oil and gas contaminated water generated as a byproduct in the oil and gas industry, industrial waste. It is the most substantial amount of pollution sources in the oil and gas industries. Produced water can be naturally occurring water, which is trapped during the underground formations in the reservoir rock. Figure 1.1 illustrates a reservoir formation, where formation water occurred naturally. Another source of produced water in the oil and gas industry is water injection. During this process, water is injected into the reservoir to increase pressure, consequently, to achieve maximum oil recovery. This water turns into produced water when it is mixed with hydrocarbons and flows back to the surface (Fakhru'l-Razi et al., 2009). Daily produced water production in the world is about 250 million barrels, whereas oil production is around 85 million barrels (Igunnu and Chen, 2012). Consequently, the ratio of daily produced water production to oil production is 3:1. Produced water contains salts, inorganic ions, toxic organic compounds, metals, naturally occurring radioactive materials causing potential harm to the environment and human health. It is chemically complex as it has been in contact with the underground oil and gas formations for centuries before it is released in the surface area. The content of produced water depends on geology formation.

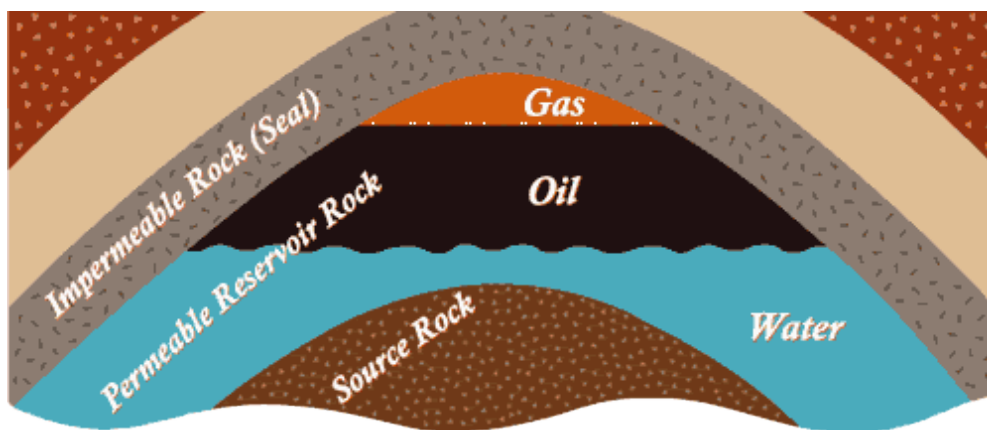


Figure 1.1 Reservoir formation (Downey, 2016)

The produced water compounds are more toxic and harmful to the environment than crude oil, and it may contaminate natural resources (Wardley-Smith, 2012). When produced water is discharged into the natural environment, its hazardous compounds at elevated concentrations are the most significant environmental concern. Since in offshore oil and gas operations, produced water is mostly discharged into the marine environment, and it may affect

the natural environment, and the living organisms would be exposed to the toxic constituents. In the end, moving up the top of the food chain, it could be the risk to human life while exposing to these compounds by consuming the biological species such as fishes.

Therefore, many countries have developed strict environmental regulations and standards for produced water discharge. United States Environmental Protection Agency (USEPA) developed regulations for the onshore, offshore, and coastal areas in 1979, and amended these regulations in 1993, 1996, 2001, and 2016. Based on EPA's effluent limitations for the Oil and Gas Extraction Point Source, the daily maximum limitation for oil and grease is 42 mg/l, and the average monthly limitation is 29 mg/l (US EPA, 2019).

Table 1.1 USEPA produced water effluent limitations (US EPA, 2019)

Subcategory	Year Promulgated	Level of Limitation	Effluent Limitation (for oil and grease)
Offshore	1979	BPT	48 mg/l monthly avg., 72 mg/l daily max
	1993	BAT/NSPS	29 mg/l monthly avg., 42 mg/l daily max
Onshore	1979	BPT	No discharge
Coastal	1979	BPT	48 mg/l monthly avg., 72 mg/l daily max
	1996	BAT/NSPS	No discharge, except for Cook Inlet, Alaska. In Cook Inlet: 29 mg/l monthly avg., 42 mg/l daily max
Agricultural and Wildlife Water Use	1979	BPT	35 mg/l daily max
Stripper Wells	1979	BPT	Reserved

Note: BPT – Best Practicable Technology; BAT – Best Available Technology; NSPS - New Source Performance Standards

Table 1.2 Produced water effluent limitations by countries (CAPP, 2001)

Country	Effluent limits	Reporting routine
USA	29 mg/l monthly avg., 42 mg/l daily max	Annual
Canada	40 ppm monthly avg., 80 ppm 2-day avg.	Monthly
UK	40 ppm monthly avg. 30 ppm annual avg.	Monthly O&G Annual comprehensive

In offshore oil and gas operations produced water is mostly discharged directly to the ocean after meeting the environmental regulations and standards by applying treatment technologies. While in onshore operations, the vast majority of generated produced water is managed by injecting it back to the wells. The other small portion is discharged, reused for other purposes, or evaporated (Clark and Veil, 2009). The main differences between offshore and onshore produced water management are the weight and space limitations in offshore operations, which affect the overall efficiencies of the treatment. Additionally, the difference in environmental regulations and standards, volume generated during the production as well as the difference in targeted pollutants lead to the different management approaches. While onshore operations are mostly targeted at decreasing the salt content, in offshore oil and operations oil and grease content are the primary concern (Zheng et al., 2016).

1.2 Aims and objectives

Most studies related to produced water management are focused on produced water treatment techniques. Minimal work has been conducted on the integrated risk assessment of produced water and taking the risks into account during the decision-making process. However, to evaluate existing standards and potential impacts on the environment, potential hazards and the associated risks should be considered in the decision-making process of produced water management. A risk-based approach can be used as a framework to select and design an effective produced water management strategy (a combination of treatment and reuse techniques). There is a minimal number of studies on the development of a systemic approach for produced water management. To overcome the above problems and fill the knowledge gap, this work aims to:

- Develop a framework for risk-based management of produced water;
- Develop an approach for assessing integrated risk (environmental, technological and economic risks) associated with treatment and reuse of produced water; and
- Demonstrate the application of the risk-based approach through Thunder Horse Oil Field study

1.3 Thesis structure

The rest of the work is organized as follows. Chapter 2 gives a brief overview of the composition of produced water as well as a possible combination of produced water reuse technologies and treatment methods with details descriptions is given. Chapter 3 is being devoted to the proposed methodology for risk-based management of produced water, the application of the methodology to a case study is presented in chapter 4. In chapter 5, the results

of the application are presented. Finally, conclusions from this study are summed up in chapter 6 with recommendations for future work.

1.4 Scientific contribution and the workflow of the study

Table 1.3 contains the contribution to knowledge and professional development that have emerged during my master program by means of journal publication and conference presentation and seminar presentation. Figure 1.2 is the flow chart showing the framework for the study and how the contents of Table 1.3 are linked.

Table 1.3 The contribution to knowledge and professional development during the master's program

February, 2020	<i>Journal publication</i> Submitted a paper based on this research to Process Safety and Environmental Protection journal. The paper is currently under review.	<i>Scientific contribution</i> Oil spill models are integrated with risk assessment to frame a risk-based approach for produced water management.
August, 2019	<i>Conference presentation (partial results from MSc thesis)</i> Kaby, A. and Yang, M. (2019). A Risk-Based Approach to Produced Water Management in Oil and Gas Operations. iWISE 2019 International Conference on Water, Informatics, Sustainability, and Environment, Ottawa, Aug 2019	<i>Scientific contribution</i> Environmental, technical, and economic risks are integrated to support decision-making of produced water management.
March, 2019	<i>Seminar presentation</i> Presented literature review in research seminar course	<i>Scientific contribution</i> An integrated framework for the risk-based approach to produced water treatment and management is proposed.

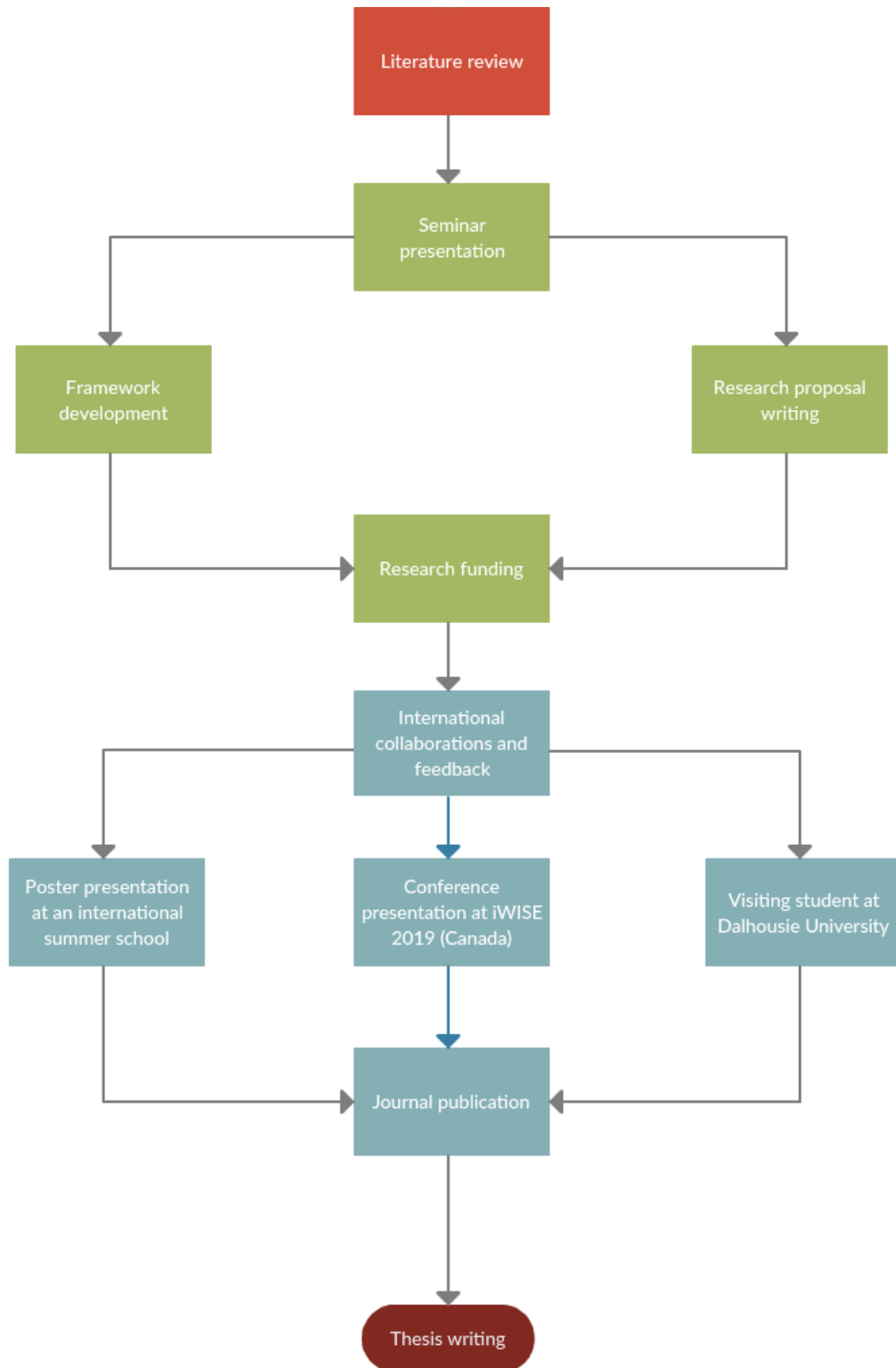


Figure 1.2 The workflow

Chapter 2 – Literature Review

2.1 The composition of produced water

Produced water properties depend on the geochemistry, geological age, and depth of the formation in addition to the chemicals added during the production process. Produced water contains various naturally occurring compounds, including salts and inorganic ions, organic compounds, metals, and naturally occurring radioactive materials (NORM). Detailed discussions of each compound are presented in the following subsections.

2.1.1 Salts and inorganic ions

The range of salts concentration of produced water can be broad (from a few parts per thousand to 300 parts per thousand, whereas seawater salinity is ~35 ‰). Since, in most cases, the amount of salts in produced water is higher than seawater, their density is higher as well. The produced water contains the same or higher amount of salts and inorganic ions as seawater with an abundance of chloride and sodium ions. The oral ingestion of a large quantity of sodium and chloride ions may result in vomiting, gastrointestinal tract irritation, respiratory distress (Rowe et al., 2009).

Table 2.1 The mean concentrations of different inorganic ions and elements in produced water and seawater (Lee and Neff, 2011)

Elements/Ions	Produced Water, ppm	Seawater, ppm
Salinity	5 000 – 300 000 000	35 000
Sodium	23 000 – 57 300	10 760
Chloride	46 100 – 141 000	19 353
Calcium	2 530 – 25 800	416
Magnesium	530 – 4 300	1 294
Potassium	130 – 3 100	387
Sulfate	210 – 1 170	2 712
Bromide	46 – 1 200	87
Strontium	7 – 1 000	0.008
Ammonium	23 – 300	-
Bicarbonate	77 – 560	142
Iodide	3 – 210	167
Boron	8 – 40	4.45
Carbonate	30 – 450	-
Lithium	3 – 50	0.17

2.1.2 Organic compounds

The organic compounds content in produced water ranges from 0.1 ppm to 11 000 ppm. The organic acids in produced water are mostly low molecular weight acids, such as formic acid and propionic acid. Benzene, toluene, ethylbenzene, and xylenes (BTEX) are the most common hydrocarbons in produced water. Among BTEX compounds, toluene is more widespread in produced water comparing to other compounds. However, BTEX evaporates quickly from seawater when it is discharged, whereas polycyclic aromatic hydrocarbons are persistent in the marine environment. PAHs are of grave concern because they can cause DNA damage, defects of cardiac functions, embryotoxicity, etc. (Bakke et al., 2013). Concentrations of naphthalene and phenanthrene are sometimes higher than trace concentration (Reed and Johnsen, 2012). Organic compounds result in reproductive disorder, loss of membrane integrity, and DNA damage in marine ecological entities. Tollefsen *et al.* (2011) reported in their study that alkylphenols and PAHs mixtures modify Atlantic cod's endocrine physiology.

Table 2.2 The concentration range of different organic components in produced water (Lee and Neff, 2011)

Component	Concentration range, ppm
Organic carbon	0.1 – 11 000
Organic acids	0.001 – 10 000
Aliphatic hydrocarbons	17 – 30
Benzene, toluene, ethylbenzene, and xylenes (BTEX)	0.068 – 578
Polycyclic aromatic hydrocarbons (PAH)	0.04 – 3
Steranes/triterpanes	0.14 – 0.175
Ketones	1 – 2
Phenols (primarily C ₀ -C ₅ -phenols)	0.4 – 23

2.1.3 Metals

Produced water contains several metals, and it differs depending on the region where it is generated. The concentration of some metals is higher in produced water comparing to seawater. The primary metals found in produced water are barium, iron, manganese, copper, and zinc. Lead is a toxic metal that enters a body through ingestion, inhalation, and skin absorption and can be accumulated in tissue. It affects most organs in the human body, especially kidneys and brains (Tarrago and Brown, 2012). Chromium is also toxic and water contaminated with chromium, which results in skin irritation, livestock death, etc.

Table 2.3 The concentration of different metals in produced water and comparison with seawater (Lee and Neff, 2011)

Metal	Produced Water, ppm	Seawater, ppm
Arsenic	0.09	0.001 – 0.003
Barium	13.5	0.003 – 0.034
Cadmium	0.01	0.000001 – 0.0001
Chromium	0.001 – 0.01	0.0001 – 0.00055
Copper	0.137	0.00003 – 0.00035
Iron	12 – 28	0.000008 – 0.002
Lead	0.0001 – 0.045	0.000001 – 0.0001
Manganese	1.3 – 2.3	0.00003 – 0.001
Mercury	<0.01	0.00000007 – 0.000006
Molybdenum	<0.001	0.008 – 0.0013
Nickel	0.0001 – 0.42	0.0001 – 0.001
Vanadium	0.0001 – 0.0006	0.0019
Zinc	0.01 – 26	0.000006 – 0.00012

2.1.4 Naturally occurring radioactive materials (NORM)

NORM can be found in produced water and radium-226, and radium-228 are mainly the most frequent among them. Radium is derived from the radioactive decay of uranium-238 and thorium-232 associated with certain rocks and clays in the hydrocarbon reservoir (Lee and Neff, 2011). When radium decays, it emits alpha and gamma rays, and exposure to radium causes cancer.

Table 2.4 The concentration of different radioactive elements in produced water compared to seawater (Lee and Neff, 2011)

Radioactive element	Produced water, pCi/l	Seawater, pCi/l
²²⁶ Ra	0.054 – 32 400	0.027 – 0.04
²²⁸ Ra	8.1 – 4 860	0.005 – 0.03
²²⁴ Ra	13.5 – 1 080	0.0002 – 0.008
²³⁸ U	0.008 – 2.7	1.1
²³² Th	0.008 – 0.027	0.003
²¹⁰ Pb	1.35 – 5 130	0.026 – 0.12
²¹⁰ Po	0.005 – 0.17	0.018 – 0.068

2.2 Produced water treatment and reuse technologies

General produced water treatment plant design consists of the following stages of treatment:

- Primary oil removal
- Secondary physicochemical oil removal
- Biological purification
- Tertiary treatment

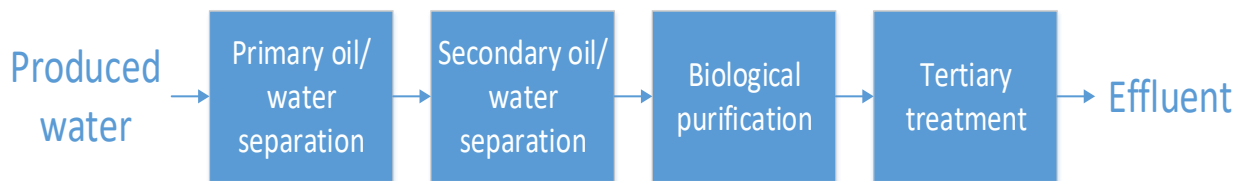


Figure 2.1 Produced water treatment stages

Although there are different techniques for produced water treatment, each technique may remove only a certain type of contaminants with its own pros and cons. That is why there is a need to compare different treatment techniques in terms of environmental, economic, and technical efficiencies. For example, in case of BTEX, hydrocarbons removal technologies, dissolved organics adsorption on activated carbon, copolymers, and organoclay, C-TOUR, dissolved air precipitation (DAP), biological aerated filters (BAF), and activated sludge have been suggested by different researchers (Al-Ghouti et al., 2019; Fakhru'l-Razi et al., 2009). C-TOUR, Dissolved air precipitation (DAP), and Biological aerated filters (BAF) are not effective due to their low removal efficiencies. Even though the absorption process may reduce the hydrocarbons concentration lower than defined water quality standards, activated sludge is more efficient because it can remove 98-99% of total petroleum hydrocarbon, yet it is simple, cheap, and green.

By comparing different treatment technologies, the following technologies are selected as they have higher contaminants removal efficiencies, technically and economically viable and they are still subject to further research: the EPCON Dual compact flotation unit for primary and secondary physicochemical oil removal, activated sludge as a biological purification technique, and sand filters for removal of dissolved matter and metals removal.

2.2.1 Primary and secondary physicochemical oil removal

The primary oil separation process for produced water is generally carried out by the artificial gravity process. Centrifuges and cyclones can be used, causing an increased gravity field for primary oil separation. Based on the difference in density, hydrocyclones are used to separate oil and suspended solids from produced water and can reduce oil concentration down to 10 ppm. They do not need energy or chemicals for their operation and do not require any pre- or post-treatment stages. The use of small and compact hydrocyclones is preferable in offshore oil and gas operations due to space limitations (Nasiri and Jafari, 2017).

For primary and secondary physicochemical oil removal EPCON Dual compact flotation unit (CFU) can be used. The EPCON CFU is a separator that can remove oil from produced water (flow rate is between 500 bbl/d [$3 \text{ m}^3/\text{h}$] and 150 000 bbl/day [$1000 \text{ m}^3/\text{h}$]). It can reduce the concentration of oil in produced water down to 5 ppm and can be used for total oil removal. The removal efficiency of Epcon Dual compact flotation unit for polycyclic aromatic hydrocarbon is up to 83%, whereas, for alkylated phenols and BTEX, the removal rate is up to 88% (Maelum and Rabe, 2015).

Benefits and some features of the treatment method are:

- Saves space significantly (50% smaller than conventional techniques)
- Increased reliability
- Streamlined and more efficient operations
- Enhanced safety
- Higher performance of oil removal
- Long operating life
- Minimized maintenance and simplified control requirements
- No external energy is required

2.2.2 Biological purification

Biological treatment methods are commonly used treatment technologies for dissolved organic compounds removal in oil and gas operations. The most widely used and practiced process in the industry is activated sludge. Activated sludge is a reliable and the most effective available treatment technique among all of the biological treatment methods. In this method, the organic material is used by microorganisms as an energy and carbon source for microbial growth, and they are transformed into cell tissue, oxidized products (mostly CO_2), and water

(EcA, 2010). The removal efficiency of total petroleum hydrocarbon (TPH) is 98-99% in the activated sludge treatment (TPH concentration <1 ppm) at a solids retention time (SRT) of 20 days (Tellez et al., 2002).

2.2.3 Tertiary treatment

Tertiary treatment is designed to meet more strict standards and for removal of:

- Total suspended solids (TSS)
- Dissolved and suspended metals
- Trace organics such as PAHs
- Chemical oxygen demand (COD)

Sand filters are a stage of the water treatment process to remove metals and fine solids with the lower settlement capacity. Before removing different metals from produced water by using sand filtering, a pretreatment process should be considered. This pretreatment usually contains the following three steps:

- (1) Adjustment of pH to start the oxidation reaction
- (2) Aeration to increase the concentration of dissolved oxygen (e.g. in case the iron is available in the solution and in the ferrous form, it reacts with oxygen and precipitates as a ferric salt)
- (3) Solid separation by providing adequate retention time to settle precipitated solids (Ray and Engelhardt, 2012).

This process allows produced water to pass through a filter bed comprised of a layer of anthracite over sand. The larger particles are trapped by the anthracite, whereas the finer solids are held up in the sand.

2.3 Comparison of the selected produced water treatment technologies

The selected treatment techniques (defined in Table 2.5) can remove more than 85% of their target pollutants, are economically viable, and more efficient compared to other traditional treatment methods. These techniques can be used in series to treat produced water. Firstly, EPCON Dual compact flotation unit (CFU) should be used to remove oil and total petroleum hydrocarbon decreasing its concentration down to 5 ppm. Then activated sludge can be used to treat produced water and reduce oil and hydrocarbon concentration further. Considering the concentration of high metals concentration in produced water, sand filters should be used subsequently to remove metals and fine solids to meet standards. The main advantage of the

selected techniques is high removal percentage, whereas the disadvantage of these techniques is sludge generation in some treatment processes.

Table 2.5 Comparison of the selected produced water treatment technologies in terms of environmental, economic, and technical efficiencies

Treatment methods	Environmental efficiency	Economic efficiency	Technical efficiency
<i>Primary and secondary physicochemical oil removal</i>			
EPCON Dual compact flotation unit (CFU)	50% higher oil removal efficiency compared to conventional technologies; 83% PAHs and 88% BTEX can be removed, reduces the oil concentration down to 5 ppm	Long operating life, minimized maintenance and no external energy is required	Increased reliability, streamlined and more efficient operations, simplified control requirements
<i>Biological purification</i>			
Activated sludge	98-99% total petroleum hydrocarbon removal (TPH concentration <1 ppm)	Operating cost is low	Simple, green, generates sludge waste
<i>Tertiary treatment</i>			
Sand filters	Metals and fine solids removal	Economically viable	Sand filter models need to be constructed due to the different grain sizes and shapes

2.4 Produced water reuse technologies

Reuse of produced water is another viable option in water management, which helps to decrease the demand for water. Produced water can be a reusable resource, and it can be reused in different fields. For example, the re-injection of produced water into an underground formation to achieve maximum oil recovery is a common reuse technique. Using the produced water for agricultural purposes as long as its quality is acceptable or it is appropriately treated is another possible option. Additionally, produced water can be used in industry, e.g., platform washing, and ship balancing. In the areas, where there is a scarcity of water, produced water could satisfy the water demand for many industrial applications. For instance, it could be used to control the dust on dirt roads or control the fire in the areas experiencing water deficiency (Veil, 2011).

Chapter 3 – Methodology

3.1 A risk-based framework to produced water management

Since produced water composition is varied in different regions, the application of one particular treatment technique only is not viable. In this case, developing a framework in assessing and selecting the best combination of treatment and reuse techniques is required. A risk-based approach is a methodology that relies on quantitative estimation of potential hazards to evaluate and support the decision-making process. The advantage of this approach is examining and selecting the best treatment option for a particular scenario by identifying and prioritizing the risk. In the developed risk-based approach, each technique should be evaluated in terms of different risks associated with produced water management. These risks include environmental risks, which show impacts on the environment and human, as well as economic risks, i.e., if treatment methods are economically justified, and technical risks, which cover failure modes and effects of different processes, designs, and systems.

This framework proposed in this study integrates the risk measures with produced water treatment and reuse techniques. To manage produced water discharges, environmental, economic, and technical risks should be appropriately assessed and utilized in the decision-making process. The proposed risk-based framework (Figure 3.1) provides a schematic process to implement risk-based management of produced water during oil and gas operations. The main steps of the framework will be described step-by-step in the following sections.

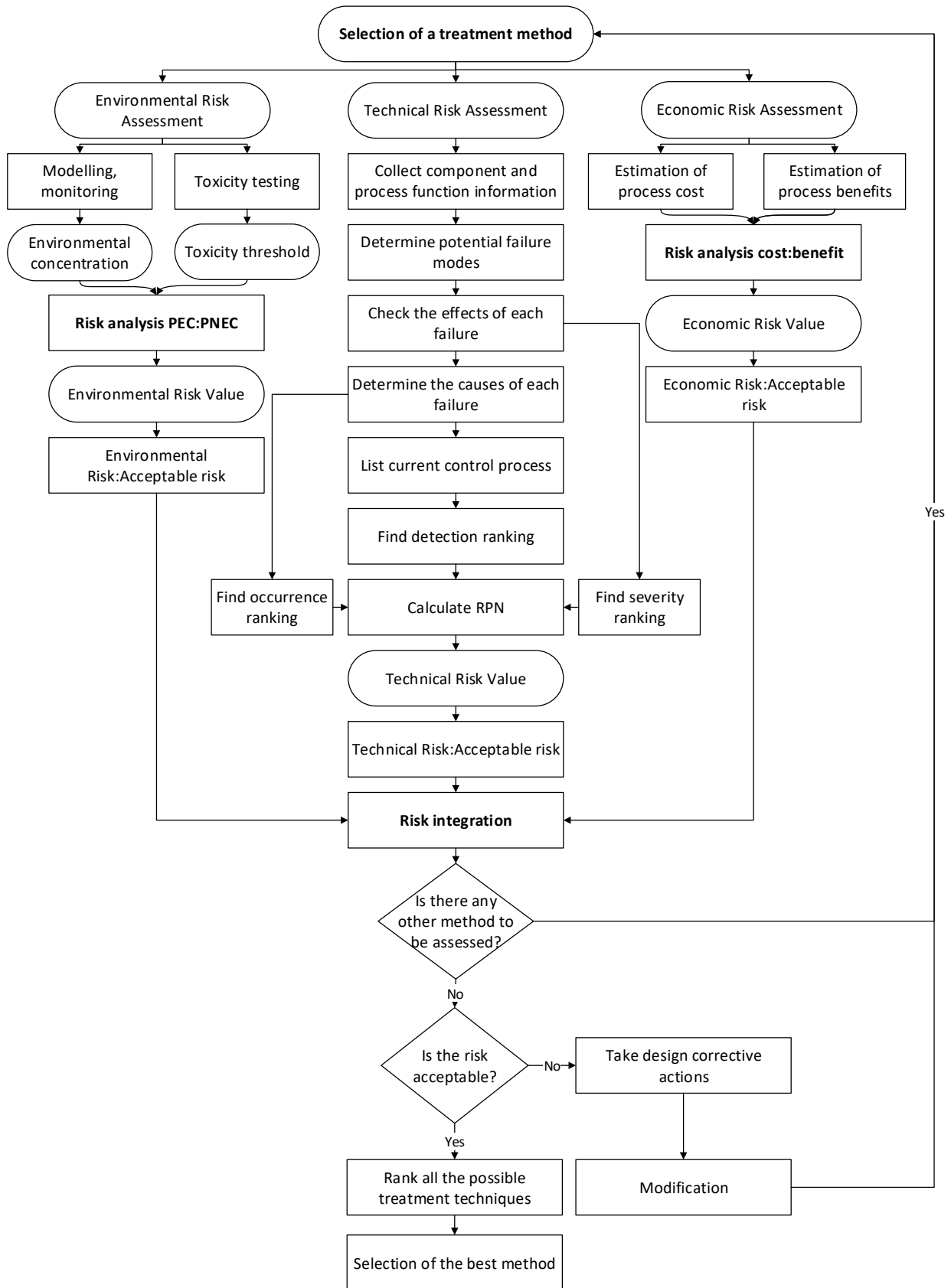


Figure 3.1 Risk-based management procedure of produced water

3.2 Environmental Risk Assessment by using Dose-related Risk and Effects Assessment Model

A three-dimensional, time-dependent, multiple component numerical model DREAM (Dose-related Risk and Effect Assessment model) (SINTEF, 2019) is a software integrated with OSCAR (oil spill model) in Marine Environmental Modelling Workbench (MEMW) that is designed as a computerized decision support tool for the rational environmental risk management of operational discharges in the marine environment. SINTEF has developed it in cooperation with Shell, Total, ExxonMobil, ConocoPhillips, Petrobras, British Petroleum, StatoilHydro, and ENI. The model can simulate transport and fate, exposure, uptake, dose, and effects of chemical mixtures. Chemical components of the mix are described by physical, chemical, and toxicological parameters. Governing physical-chemical processes are:

- Transport and dilution both horizontal and vertical;
- Dissolution of droplet form;
- Volatilization of the surface phase or dissolved forms;
- Adsorption/desorption of particles, and settling;
- Biodegradation;
- Sedimentation.

3.2.1 Physical-chemical fate modeling

Predicted Environmental Concentration (PEC) is a basis for risk assessment in DREAM, and it can be calculated by simulation of the transport and fate of the pollutants in the environment. DREAM solves the generalized transport equation:

$$\frac{\delta C_i}{\delta t} + \vec{V} \cdot \vec{\nabla} C_i = \vec{\nabla} \cdot D_k \vec{\nabla} C_i + \sum_{j=1}^n r_j C_i + \sum_{j=1}^n \sum_{i=1}^n r_{ij} C_i \quad (1)$$

Where,

C_i – i^{th} chemical concentration in the release

t – time

\vec{V} – advective transport vector

$\vec{\nabla}$ – gradient operator

D_k – turbulent dispersion coefficient in $k = x, y, z$ directions

r_j – process rates of the following processes:

- Mass addition from the continuous release
- Evaporation from surface slicks
- Emulsification of surface slicks

- Deposition from water surface onto the coastline
- Entrainment and dissolution into the water column
- Deposition to bottom sediments from the water column
- Removal from the water column to water surface/water column
- Mass removal by cleanup

r_{ij} – degradation term (mass transfer from one component to another) (Reed and Hetland, 2002)

Chemical concentrations are calculated from the space- and time-variable pseudo-Lagrangian particle distribution. There are two types of these particles: a) dissolved substances, and b) oil droplets (or particles with non-neutral buoyancy). Oil droplets or particles with non-neutral buoyancy are pseudo-Lagrangian in a way that they may settle or rise according to the physical characteristics but do not move stringently with the currents.

In DREAM, the physical environment is defined by the following parameters:

- Coastline
- Currents
- Bathymetry
- Sea state
- Winds
- Sea temperature, and salinity

The contaminants' behavior in DREAM is governed by the processes depicted in Fig 3.2.

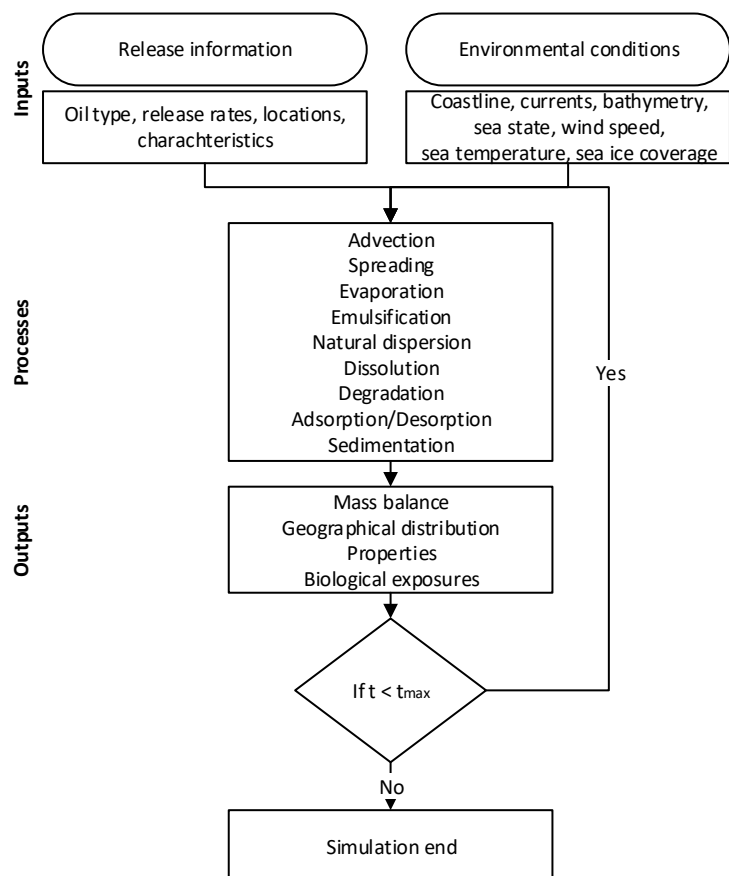


Figure 3.2 The general layout of the *DREAM* model (regenerated based on Reed and Hetland, 2002)

Advection and *dispersion* of dissolved and entrained hydrocarbons are governed by mean local velocity (the sum of tidal, climatological, wind-driven and wave-driven components), and a turbulent random component. Horizontal turbulence is a function of the contaminant puff's age, whereas vertical turbulence is a function of depth and wave speed (wave height).

Pollutants that are close to the surface of the sea may *evaporate* into the atmosphere. The procedure of mass transfer rate calculation for the contaminants is outlined by (Lyman, 1990).

Adsorption is an essential process in the pollutants' transport and fate in the marine environment because it sets the pollutant's partitioning extent between the dissolved phase and the suspended particulate phase. Hence, it controls toxic effects and the removal rate from the water column to the sediments. Dissolved and particulate-adsorbed states partitioning is calculated based on the linear equilibrium theory. The fraction of contaminant adsorbed to suspended particulate settles down with ambient particles.

The *degradation* process in the water column and sediments is a process of first-order decay and can produce intermediate metabolites. Degradation transformations are shown schematically in Fig. 3.3 in the case of aliphatic hydrocarbons. Even though it is known that the products of degradation may be more toxic and soluble than the initial components, information about metabolic products' characteristics and rates are not sufficient to simulate this complex process confidently.

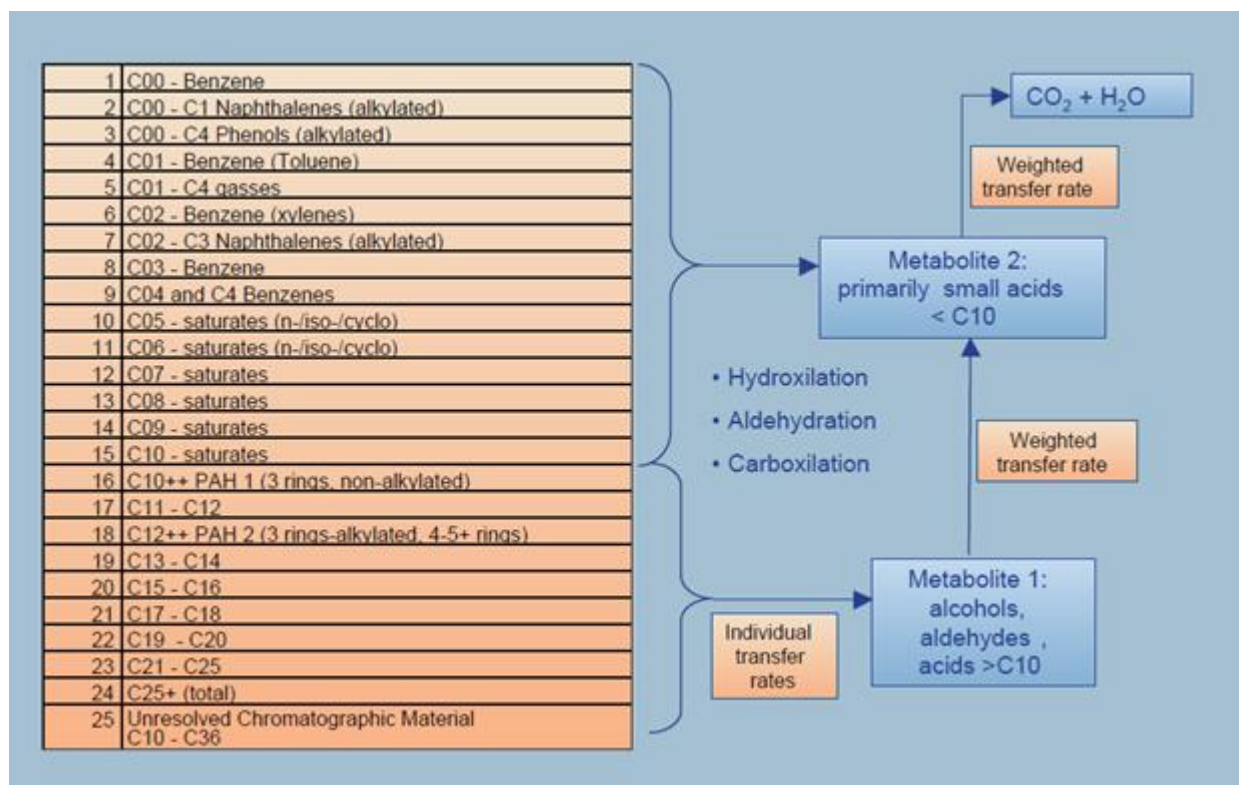


Figure 3.3 Degradation transformations for hydrocarbons (Reed and Hetland, 2002)

The simulation results are saved for further viewing at discrete time steps.

Environmental Risk Assessment is a commonly used methodology to estimate and assess the potential environmental consequences due to operational discharges. DREAM performs risk assessment based on the Environmental Impact Factor (EIF) concept (PEC/PNEC approach), meaning that exposure level represented by a potential environmental concentration (PEC) is compared to toxicity threshold (sensitivity) inferred from predicted no-effects concentration (PNEC) (Van Leeuwen *et al.*, 1996; Jager *et al.*, 2001). Also, weighting factors are applied for the EIF calculation taking into account the accumulative properties and persistence of compounds on the basis of their bioaccumulation tendency (LogP_{ow}) and potential to biodegrade (BOD, 28d), respectively. Toxicity data about long-term marine species exposure to the produced water compounds (metals, aromatic hydrocarbons, organic acids,

alkylphenols) and additive chemicals (e.g. corrosion inhibitors) is used in order to evaluate the PNEC. If there is not enough information regarding the long-term toxicity data, then short-term toxicity data (acute toxicity) is collected (mainly for additive chemicals). The specific assumptions, procedures, and data used for the basis of PNEC calculation are described by Johnsen, Frost, Hjelsvold, and Utvik (Johnsen et al., 2000).

Table 3.1 Weighting factors and weighting criteria in EIF

Biodegradation (BOD, 28-day test)	Bioaccumulation (LogP_{ow})		
	<3	3-5	>5
>60%	1	1	1
20-60%	1	2	2
<20%	2	2	4

Both the multimedia fugacity approach (i.e., Mackay et al., 1992) and 3-D models may be used to calculate the Predicted Environmental Concentration (PEC). 3-D Fates module is used in DREAM, calculating the PEC using the PROVANN model mathematics (Reed and Johnsen, 2012).

An EIF shows 100 m x 100 m x 10 m (10^5 m^3) volume of water in which the concentration of one or more substances exceeds an ecotoxicological threshold level. The EIF calculation process is shown in Fig 3.4.

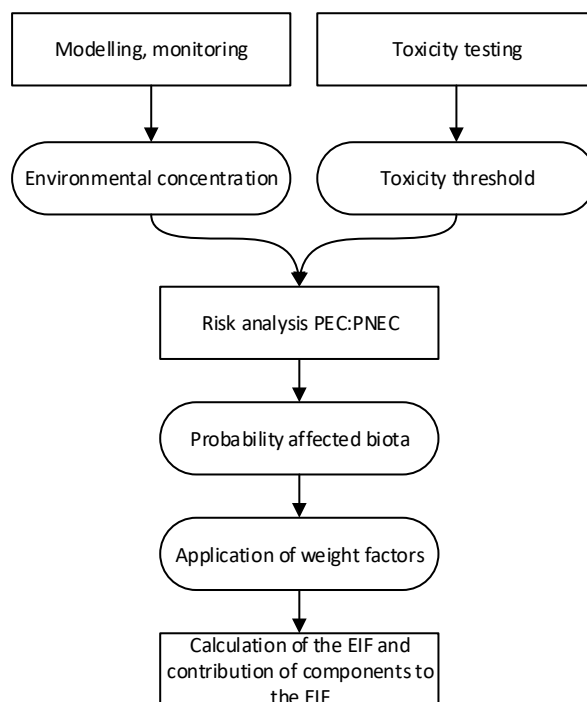


Figure 3.4 The EIF calculation scheme for produced water discharges (Smit et al., 2003)

For the EIF, produced water is divided into 10 groups of “naturally occurring” compounds that characterize it (Johnsen et al., 2000). It is assumed that the toxic and chemical properties of the substances in one group are comparable. The most toxic component within each group is selected, and its PNEC value and Species Sensitivity Distribution are set for each group as representatives based on the available toxicity data.

Table 3.2 Composition of the defined groups in produced water (Smit et al., 2003)

No.	Main group	Substances	Representative	PNEC (ppb)	Weighting factor
1	BTEX	Benzene, toluene, ethylbenzene, xylene	Benzene	17	1
2	Naphthalenes	Naphtalene + C1-C3 Alkylhomologues	Naphtalene	2,1	1
3	PAH 2-3 ring	Substances on the EPA 16 PAH list with 2-3 rings	Phenanthrene	0,15	1
4	PAH 4-ring+	Substances on the EPA 16 PAH list with 4 ring or more	Benzo[a]pyrene	0,05	2
5	Alkylphenols C0-C3	Phenol + C1-C3 alkylphenols, incl. Alkyl-homologues	Phenol	10	1
6	Alkylphenols C4-C5	C4-C5 alkylphenols, incl. Alkyl homologues	Pentylphenol	0,36	1
7	Alkylphenols C6+	C6-phenol and higher, incl. Alkyl homologues	Nonylphenol	0,04	2
8	Aliphatic hydrocarbons	Various	Heptane	40,4	2
9	<u>Metals 1</u> Zinc Copper Nickel	Zn, Cu, and Ni	Field-specific	0,46 0,02 1,22	1 1 1
10	<u>Metals 2</u> Lead Cadmium Mercury	Pb, Cd, and Hg	Field-specific	0,182 0,028 0,008	1 1 1

In general, PNEC is obtained by dividing the lowest NOEC or LC/EC50 value by an appropriate assessment factor for three trophic groups. The assessment factors should be applied to extrapolate single-species toxicity data from the laboratory to multi-species ecosystem effects (Emans et al., 1993). The following several uncertainties are considered by taking into account the assessment factors:

- Biological variance
- Short-term to long-term toxicity extrapolation
- Laboratory data to field impact extrapolation

Table 3.3 The assessment factors that are used to calculate PNEC values

Available toxicity data	Assessment factors
At least one short-term EC50 from each of three trophic levels (fish, crustaceans, and algae)	1000
Long-term NOEC from one trophic level (either fish or crustaceans)	100
Long-term NOEC from two trophic levels (fish and/or crustaceans and/or algae)	50
Long-term NOEC from at least three trophic levels (fish, crustaceans, and algae)	10

3.2.2 From PEC/PNEC to Risk

The actual risk cannot be determined by the PEC/PNEC approach because the PEC/PNEC ratio is only a qualitative indication of the risk, it does not have a meaning in a quantitative sense (Jager et al., 2001).

Karman and Reerink (1998) proposed a methodology that can convert the PEC/PNEC ratio into a real risk value. In the methodology, the variation of different species' sensitivity to a particular component is used to convert the ratio into risk measures. The sensitivity variation can be defined using a Species Sensitivity Distribution (SSD) (Posthuma et al., 2001). SSD is based on toxicity data (NOECs or LC/EC50s) for various species. It is assumed that the PNEC corresponds to the 5th percentile of the SSD, meaning that PNEC value corresponds to the 5% probability that random species are affected by contaminants when the distribution is based on long-term NOECs (Fig 3.5). The respective frequency will identify the probability of species that are affected by contaminants at any other exposure level.

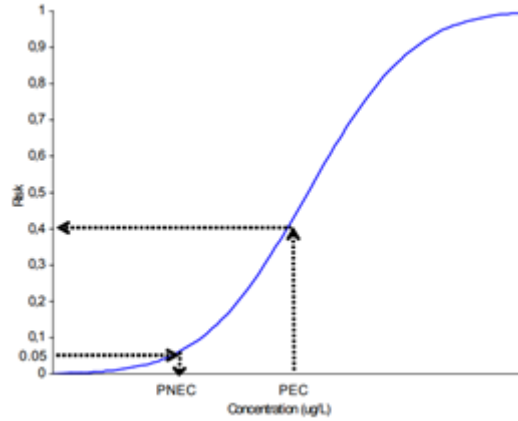


Figure 3.5 Cumulative normal distribution curve on a logarithmic scale that describes the relationship between concentration, PEC, PNEC, and risk for produced water substances (Smit et al., 2003)

When Predicted Environmental Concentration is equal to the Predicted No-Effects Concentrations (PEC/PNEC=1), the probability that a random species is affected by a contaminant is equal to 5% and the risk of adverse effects is equal to 5%.

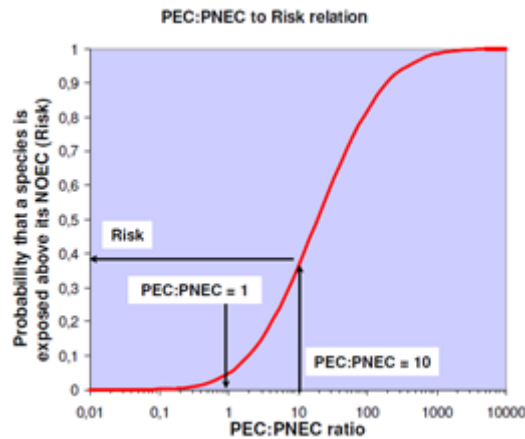


Figure 3.6 SSD scaled to the PNEC resulting in a PEC/PNEC to risk curve (Smit et al., 2005)

In order to convert PEC/PNEC into a risk value, the following formula can be used:

$$R = \int_0^{\ln PEC/PNEC} \left\{ \frac{1}{S_m \cdot \sqrt{2 \cdot \pi}} \cdot e^{-\frac{(\ln \frac{PEC}{PNEC} - X_m)^2}{2 \cdot S_m^2}} \right\} \dots \quad (2)$$

Where,

R – risk

X_m – mean of the distribution for which PEC/PNEC = 1

S_m – standard deviation of the logarithmically transformed data

PEC – exposure concentration (Smit et al., 2005)

Table 3.4 Xm and Sm value for PEC/PNEC to risk curves

No.	Main group	Group Sm	Xm
1	BTEX	1.16	1.90
2	Naphthalenes	1.43	2.35
3	PAH 2-3 ring	1.30	2.14
4	PAH 4-ring+	2.01	3.31
5	Alkylphenols C0-C3	1.28	2.11
6	Alkylphenols C4-C5	0.37	0.51
7	Alkylphenols C6+	0.77	1.27
8	Aliphatic hydrocarbons	1.37	2.25
9	<u>Metals 1</u>		
	Zinc	1.83	3.00
	Copper	1.99	3.27
	Nickel	2.26	3.72
10	<u>Metals 2</u>		
	Lead	2.08	3.47
	Cadmium	2.42	3.97
	Mercury	1.96	3.23

It is assumed that antagonistic and synergistic effects cancel each other out while combining various contaminants. For a mixture consisting of two contaminants, the following formula is used to calculate the cumulative risk:

$$R(A+B) = R(A) + R(B) - R(A) \cdot R(B) \quad (3)$$

R(A+B) – the probability that species will be affected due to both A and B contaminants

R(A) – the probability that species will be affected by exposure of contaminant A

R(B) – the probability that species will be affected by exposure of contaminant B

The generalized formula for n contaminants:

$$R_{total} = 1 - \prod_i^n (1 - R_i) \quad (4)$$

3.2.3 Validation

Validation of the model is a required stage to test the assumptions considered in the model and evaluate the uncertainties affecting results obtained by the model and model predictions. In the DREAM model, experimental validation studies, a sensitivity analysis of the model, and external scientific evaluation are performed in the validation process (Smit et al., 2003). The DREAM model calculations have been validated and compared with both field measurements and analytical solutions (Durell *et al.*, 2006; Neff *et al.*, 2006).

3.2.4 Sensitivity analysis

To identify the most affecting parameters to the EIF value calculations and evaluate the impact of concentration variations of compound groups on risk profiles and EIFs a sensitivity analysis was conducted. When the parameters set were varying in the EIF calculations, the PNEC values and biodegradation rates mainly affected the EIF, describing 40% and 25% of the EIF magnitude, respectively. Whereas the parameters were set to standard values, the most significant compound classes were the ones affecting the risk profile. Therefore, it was observed that these compounds' analytical accuracy has a great impact on the EIF calculation's accuracy (Smit et al., 2003).

3.3 Technical Risk Assessment: Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is a risk assessment tool that is designed for identifying and mitigating potential and/or known failures of the systems, designs, and/or processes. This approach is intended to enhance the safety of complex systems and provide information for the risk-based decision-making process. The analysis results could help to identify and evaluate the effects of potential failure modes as well as to improve failure modes that have a destructive impact on the system during the design and production stages. The first phase of FMEA is from the collection of information about the system's possible failure modes to the risk priority number (RPN) calculation by taking into account the risk factors of occurrence (O), severity (S), and detectability (D). The second phase actions are RPN ranking, corrective action recommendation, and design modification. At the end of FMEA, the required modifications reduce the potential failure modes numbers to the minimum. The purpose of the approach is to prioritize the failure modes of the system to focus on the most serious risk.

Risk priority number (RPN) is used to prioritize the failures for its ease and subjective evaluations of occurrence, severity, and detectability of each failure:

$$\text{RPN} = \text{O} \cdot \text{S} \cdot \text{D} \quad (5)$$

O – probability of the failure

S – severity of the failure

D – probability of not detecting the failure

To obtain an RPN of a failure mode, 10-point scale is used to evaluate three risk factors described in Tables 3.5-3.7. The higher the RPN of a potential failure mode, the greater the risk is for system reliability.

Table 3.5 Ranking for the occurrence of a failure mode (Liu et al., 2013)

Probability of failure	Possible failure rates	Rank
Extremely high: failure almost inevitable	> in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2 000	4
Low	1 in 15 000	3
Remote	1 in 150 000	2
Nearly impossible	<1 in 1 500 000	1

Table 3.6 Ranking for the severity of a failure mode (Liu et al., 2013)

Effect	Severity of effect	Rank
Hazardous	Failure is hazardous and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Comfort or convince functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Table 3.7 Ranking for the detectability of a failure mode (Liu et al., 2013)

Effect	Severity of effect	Rank
Absolute uncertainty	Design control does not detect a potential cause of the failure or subsequent failure mode, or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of the failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of the failure or subsequent failure mode	8

Very low	Very low chance the design control will detect a potential cause of the failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of the failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of the failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of the failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of the failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of the failure or subsequent failure mode	2
Almost certain	Design control will almost certainly detect a potential cause of the failure or subsequent failure mode	1

The overall process RPN for series systems can be estimated using the following equation:

$$\max (RPN) \leq x \leq 1000 - \frac{\prod_{i=1}^n (1000 - RPN)}{10^{(3n-3)}} \quad (6)$$

Considering RPN as a probability number (max RPN of 1000 is equal to 1), the upper bond of equation 6 divided by 1000 will give the technical risk value of the system.

3.4 Economic Risk Assessment

In the case of economic risks, the cost to benefit ratio will be calculated. Cost section contains the materials which are used during the treatment process such as adsorbents, chemicals' price, amount of energy spent during the process, etc. The beneficial section includes cost-saving by meeting environmental regulations. This is the cost associated with avoiding the fines and penalties, reduction of water usage by treating produced water and reusing the produced water for different applications during the operation. If the beneficial section prevails than the process cost, then the process is at low economic risk. But if the process cost value is larger than the benefit value, it means the selected treatment technique and its operation is at high economic risk.

3.5 Risk integration

After all the assessments are conducted, acceptable risk levels should be identified. The acceptable risk levels are:

- Acceptable environmental risk – 5%, because the probability that a random species is affected by a contaminant will be equal to 5% when PEC is equal to the PNEC.
- Acceptable technical risk – 0.33 or RPN of 330 based on the calculation of moderate case of occurrence, severity, and detectability.
- Acceptable economical risk – 1, on the basis when process cost equals to its benefits.

The calculated environmental, technical, and economic risk values have to be compared to the identified acceptable risk level, and the ratio of the calculated risks to the acceptable risks has to be considered. To integrate all the values from environmental, economic, technical risks into a single risk value, each factor receives a particular weight that needs to be identified by adopting the information collected using expert (professional engineers) opinions. The experts do not directly set weighting factors but rather are asked to compare pairs of risk categories in the triangle to rank and identify relative importance.

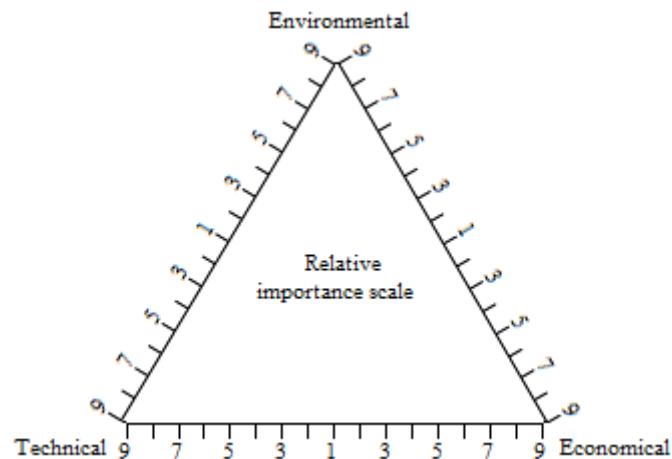


Figure 3.7 The questionnaire designed to integrate environmental, technical, and economic risks

Table 3.8 The scale of relative importance interpretation

Scale	Explanation
1	Both elements are equally important
3	One element is slightly more important over another based on expert opinion
5	One element is strongly more important over another based on expert opinion
7	One element is strongly more important over another and the dominance is shown in industrial practice
9	One element is absolutely more important over another based on magnitude difference
2, 4, 6, 8	Intermediate values used to compromise between judgements

Pair-wise comparison results can be used to build a matrix, which in turn, helps to determine the weighting factors. The calculated geometric mean of each category should be divided into the total value to calculate the weighting factor. The sum of the multiplied weighting factors to the final risk values gives us the integrated risk value of the treatment or reuse method.

$$\text{Integrated risk} = (\text{WF} \cdot \text{EnvR}) + (\text{WF} \cdot \text{TecR}) + (\text{WF} \cdot \text{EcR}) \quad (7)$$

Integrated risk can be used as a basis to guide the decision-making process on produced water management and will help to identify the processes that are at higher risks.

3.6 Selection of optimum treatment and reuse techniques

During the selection of the optimum treatment and reuse technique, two scenarios can be considered. The first scenario is when a decision-maker has different alternatives for treatment and reuse methods, and the second scenario is when there is no alternative. In the last-mentioned case, the integrated risk is calculated to check if the treatment process works properly. The integrated risk value obtained from the developed methodology can be adapted to select and justify the decision-making process. Two different scenarios would be expected:

- The integrated risk value exceeds one. It means that the associated risk is higher than defined acceptable system performance and other treatment or reuse options should be considered.
- The integrated risk equals to or lower than one, i.e., the integrated risk is equal to or below the acceptable risk level, therefore the selected process meets the standards and it implies that the process is desirable.

In the first scenario, when there are different treatment alternatives available, the treatment or reuse method that shows the lower integrated risk value (should be smaller or equal to one) is more desirable. In the second scenario, if there is no alternative, and if the integrated risk is smaller or equal to one, the reuse method can be applied. But if the integrated risk is higher than one, the other risk mitigation strategies should be considered to modify the reuse and treatment techniques.

Chapter 4 – Case Study

4.1 Application of the Developed Framework: Case Study

The case study demonstrates the detailed application of the proposed framework. In this study, information about produced water composition from 114 943 different locations all over the US is used, obtained from the United States Geological Survey (USGS). Thunder Horse Oil Field is selected as the discharge point since it is the largest offshore oil field platform in the Gulf of Mexico, and most of the data were obtained from the locations close to this region such as Texas, Louisiana, etc. The field is governed by BP plc (75%) and ExxonMobil (25%).

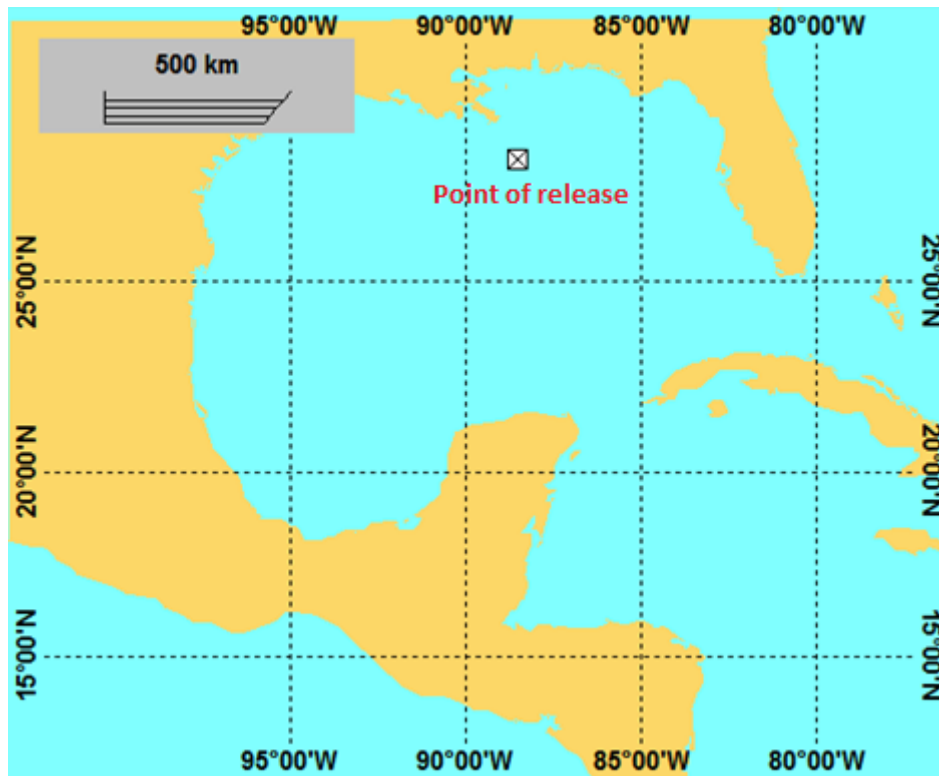


Figure 4.1 Discharge point of the study

The mean discharge rate was used for the simulation collected from the data received from the previous literature (Meinhold et al., 1996). Current fields for the Gulf of Mexico were extracted from the Global Hybrid Coordinate Ocean Model (HYCOM). The simulation time was 31 days from May 1, 2012 to May 31, 2012.

Table 4.1 Overview of the discharge information

Discharge location	88° 29.664' W 28° 6.546' N
Depth	300 m
Discharge rate	715.42 tonnes/day
Discharge duration	31 days
Salinity and temperature	75 ppt, 29°C
Pipe size and orientation	0.2 m, downwards
Chemical components	Concentration (ppm)
BTEX	48.110
Naphthalenes	0.132
PAH 2-3 ring	0.007
Zinc	11.480
Copper	0.550
Lead	29.590

All the information regarding the discharge site and physical environment are indicated in the scenario parameters. Based on buoyant plume equations Near Field release model is implemented in the model. The near-field model is applied for subsurface release, i.e. where the depth of the release point is higher than zero. It computes the formation of a density and momentum-driven plume from an underwater release. Such release can be operational in nature such as produced water or drilling fluids. Marine Environmental Modelling Workbench (MEMW) used in this study is enhanced with Plume3D - a new near field module, which can support different release sites. When Plume3D is selected, the diameter and positioning of the release pipe (see Table 4.1) should be specified. All size parameters (minimum size, maximum size, characteristic size, size-spread parameter of droplet) are disabled and estimated by the provided modules. Droplet size is calculated from the Rosin-Rammler size distribution function defined by the size parameters.

Release Site

Site Info | Near Field Info

Name:

Profile:

Location

Longitude: degree minutes

Latitude: degree minutes

Moving release location:

Time

Start: Duration: Unit:

Release

Depth: m Salinity: ppt

Rate: Temperature: °C

Repeat: Interval: days Oxygen con.: mg/l

Flux:

[Specify the name of the release site.](#)

Environmental Parameters

Grids

Wind:

Currents:

Ice:

Grid:

Province:

Background concentration

Water column:

Sediment:

Ambient data

Data source:

Period:

Upper wat. col. T (°C): Salinity (ppt):

Lower wat. col. T (°C): Air temperature (°C):

Pycnocline depth (m): Oxygen content (mg/l):

Depth, m	Salinity, ppt	Temperature, °C	Oxygen, mg/l
<input type="text"/>	<input type="text"/>	<input type="text"/>	<input type="text"/>

Suspended sediment (mg/l): High tide: Wind induced current:

Settling velocity (m/day): Tide range:

[Specify the air temperature in degrees C.](#)

Release Site

Site Info | Near Field Info

Near field model:

Release properties

Diameter, m:

Angle from north, deg: Flow velocity is super-critical

Angle from vert., deg: Use sub-sonic diam.:

Droplet size

Dispersant application Dispersant efficiency, %:

Minimum size, µm: Size-spread parameter:

Maximum size, µm: Number of data points:

Characteristic, µm:

Liquid-solid droplets

Apply agglomeration

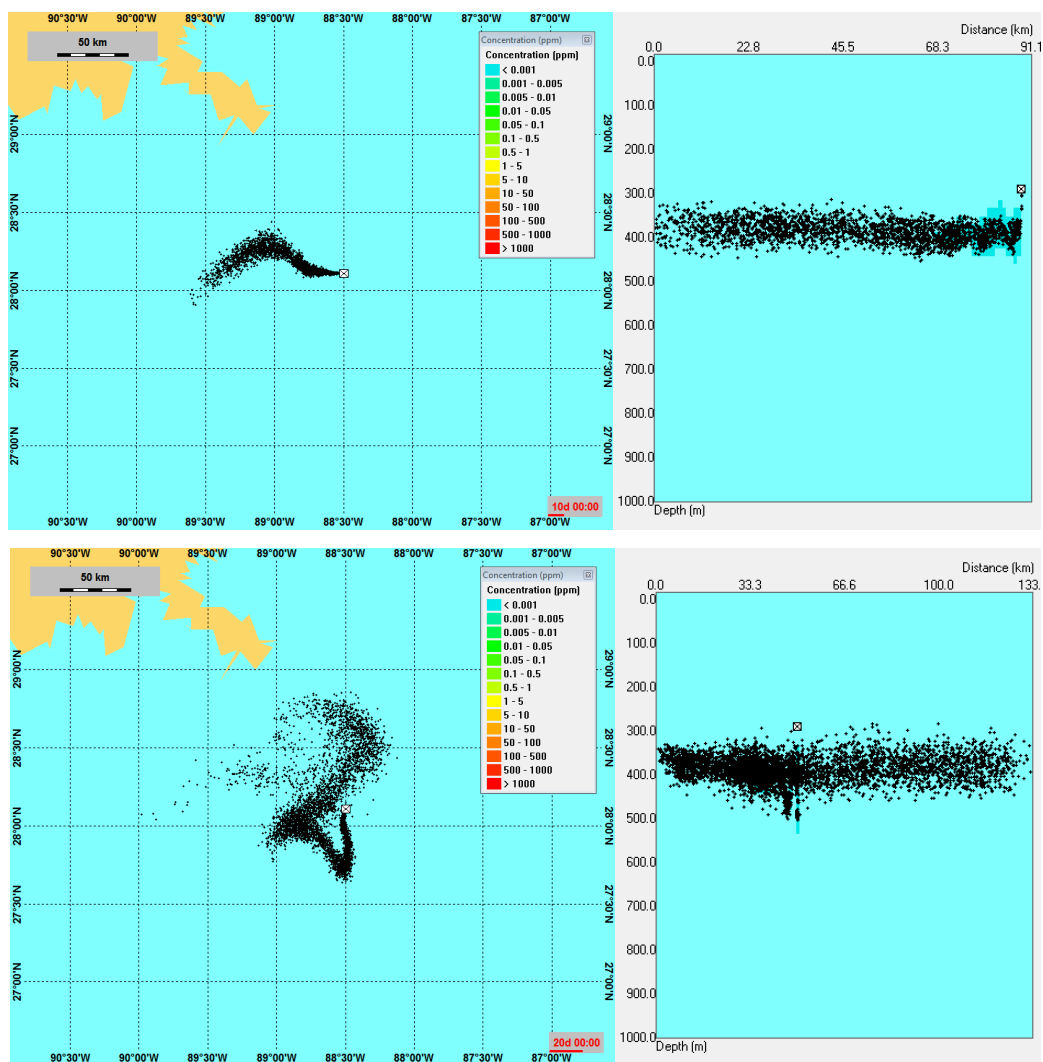
[Specify the angle of the release in degrees from the north \(clockwise\):](#)
0=north, 90=east, 180=south, 270=west.
Note: at distances over a few hundred meters from the source, the model is relatively insensitive to the release angles.

Figure 4.2 Release site, environmental parameters, and near field info for the release scenario

Chapter 5 – Results and Discussion

5.1 Environmental Risk Assessment

Environmental Risk Assessment of Produced water was conducted by using DREAM. The simulation can generate the concentration field and risk map as outputs. Horizontal and vertical cross-section of concentration fields of the produced water discharges are depicted in Fig 5.1. From the figures, it can be clearly seen that produced water particles are spread all over the gulf and plume profiles of produced water in 10, 20, 30 days show that the plume has changed its locations consistently following the current movements. The vertical profiles show that the particles of produced water go down lower than the discharge point indicating that it is not neutrally buoyant and spread out after the discharge on the bottom. The maximum concentration of subsurface contaminant was 0.065-0.07 ppb (Fig. 5.2).



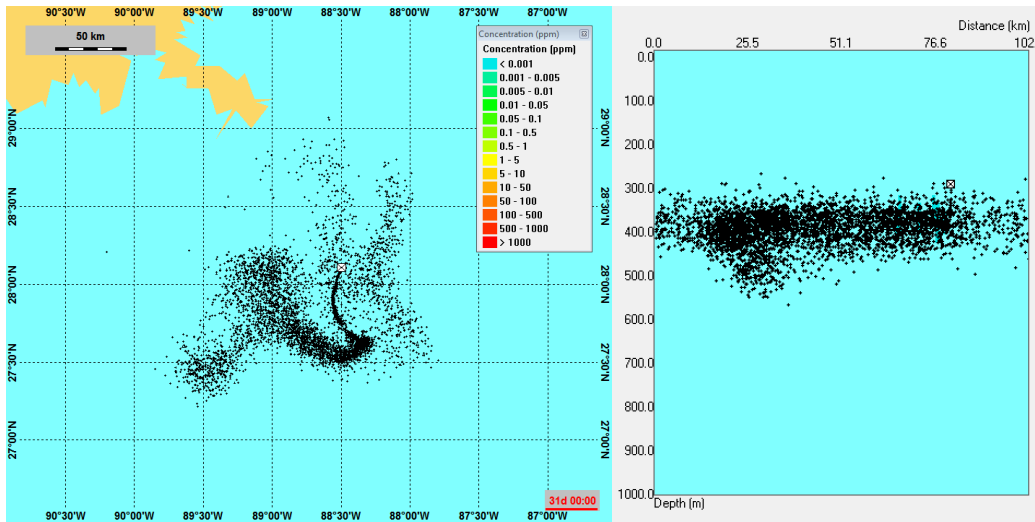


Figure 5.1 Horizontal and vertical crosssection of concentration fields of the produced water discharges in 10, 20, and 31 days

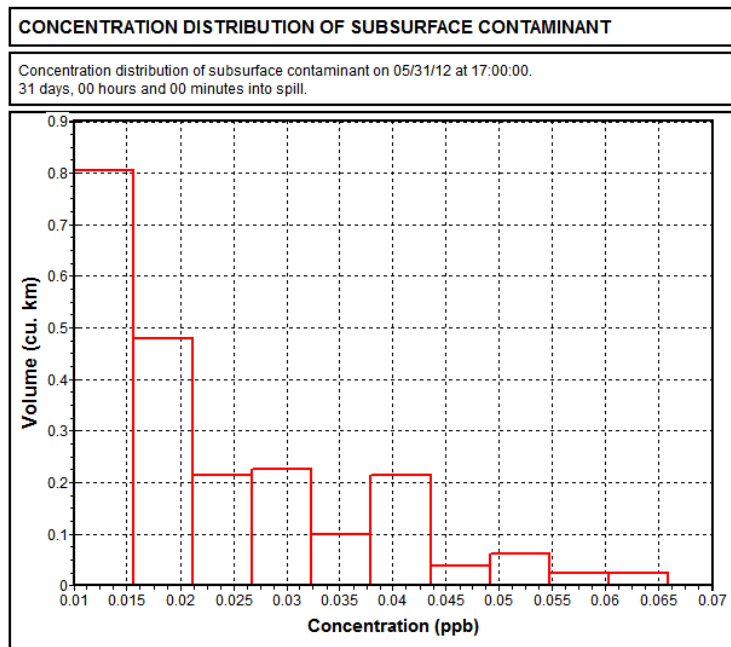


Figure 5.2 Concentration distribution of sub-surface contaminant

The risks to the environment caused by the produced water discharges are very dynamic. It also follows current movements and disturbs the environment within 50 km in different directions. The maximum risk due to produced water discharges is summarized in Fig 5.4, and it is drawn based on maximum risk recorded during the simulation in percentage in each cell.

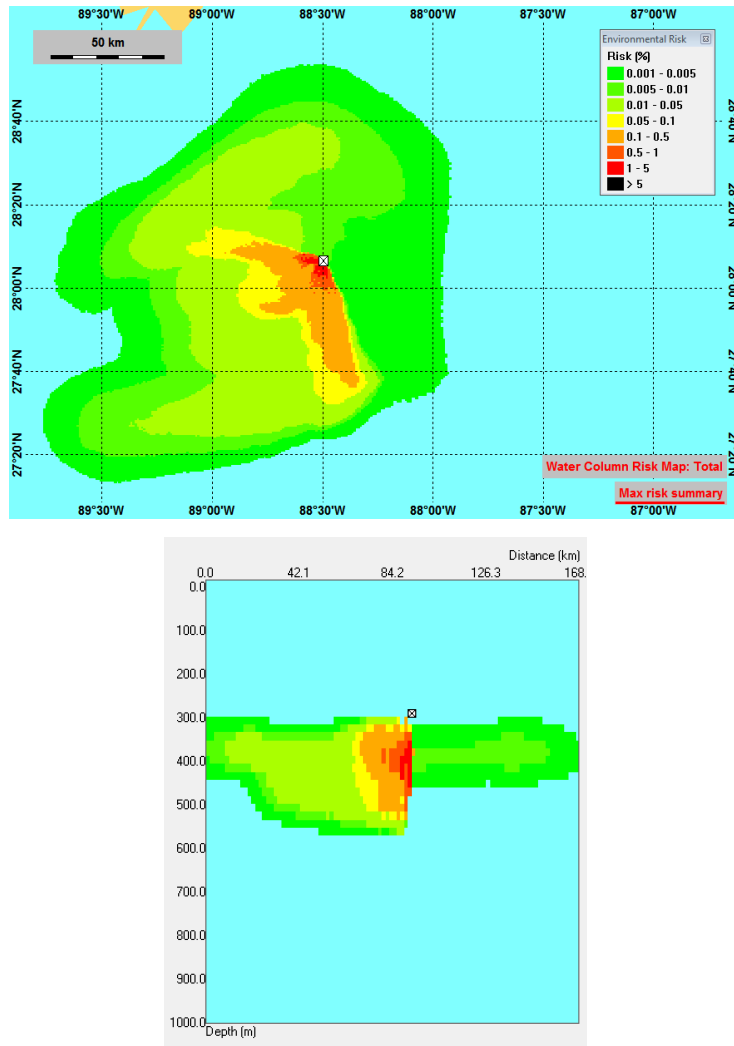


Figure 5.3. Total Risk Map of the simulated discharges

At a closer look, it can be observed that the risk values are higher in the areas closer to the discharge point. A significant risk of 5.35% was detected near the release point.

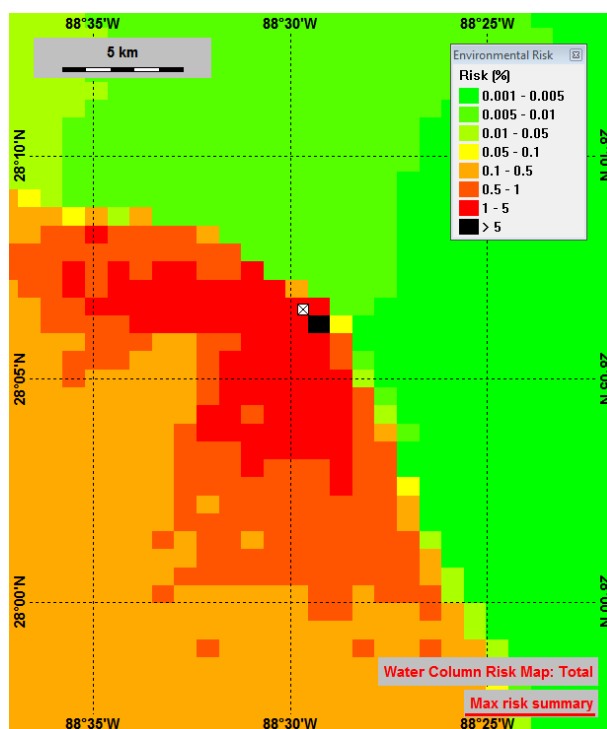


Figure 5.4 Max Risk summary of the simulated discharges within 5 km

DREAM also computes the volume of water, which is subjected to the risk value of 5% or more or $PEC/PNEC > 1$. The EIF calculated by the model is 123.9623, which indicates that 12 396 230 m³ of water has a risk of more than 5%. The contribution of each chemical used in the simulation is shown in the pie chart. From the pie chart, it can be seen that the vast majority contribution is caused by lead (80%), it is because the initial concentration of lead was more than 160 times higher than its PNEC value. This pie chart has a significant meaning since it provides vital information to a decision maker to compare alternative treatment and reuse methods for mitigating environmental risks associated with the discharge. The decision maker should be more focused on the removal technologies of the contaminants with the highest impact from the discharge. In this particular case, more considerable attention should be paid to metal removal technologies, in particular, lead removal methods. The EIF can serve as a quantitative decision support tool for environmental risk management of produced water.

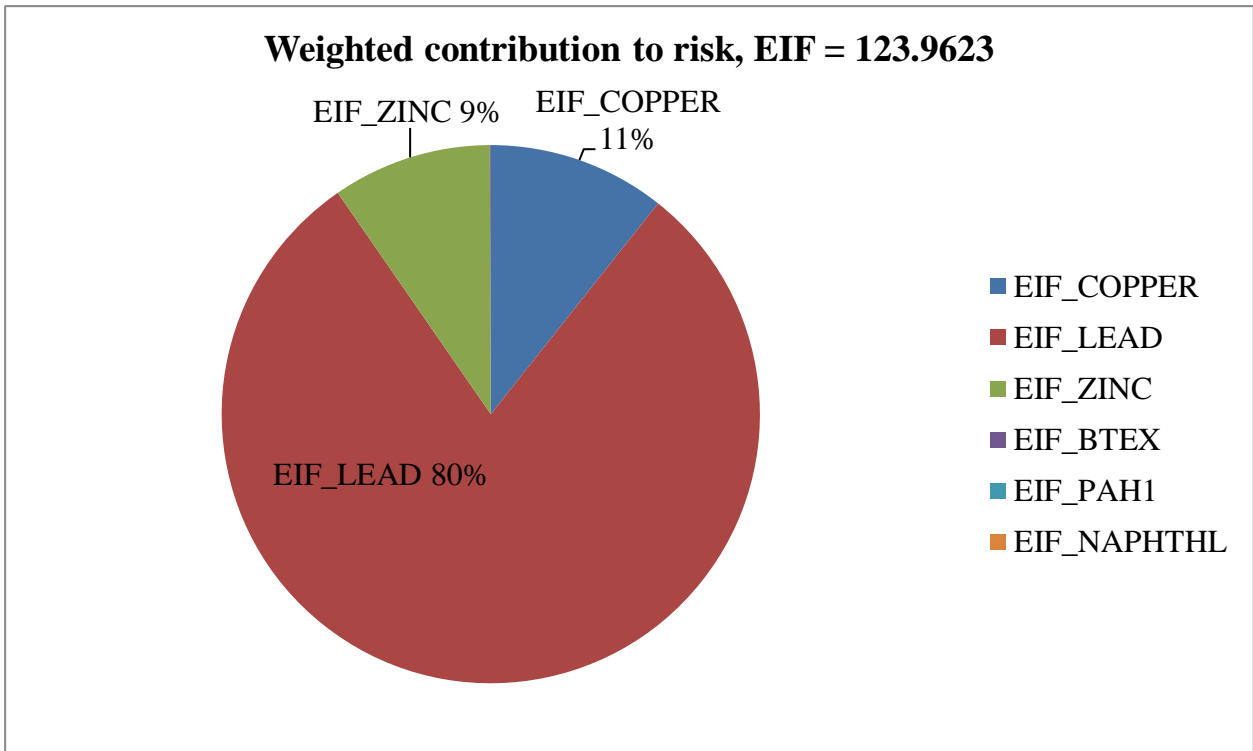


Figure 5.5 EIF value and contribution of different compounds to the total risk

Fig. 5.6 shows how the EIF has changed in percentage and weighted form throughout the simulation duration. From the figures, we can see that the maximum values of weighted EIF were observed in the period between 24 and 28 days, and the contribution of each component to the EIF was at the same range throughout the simulation period.

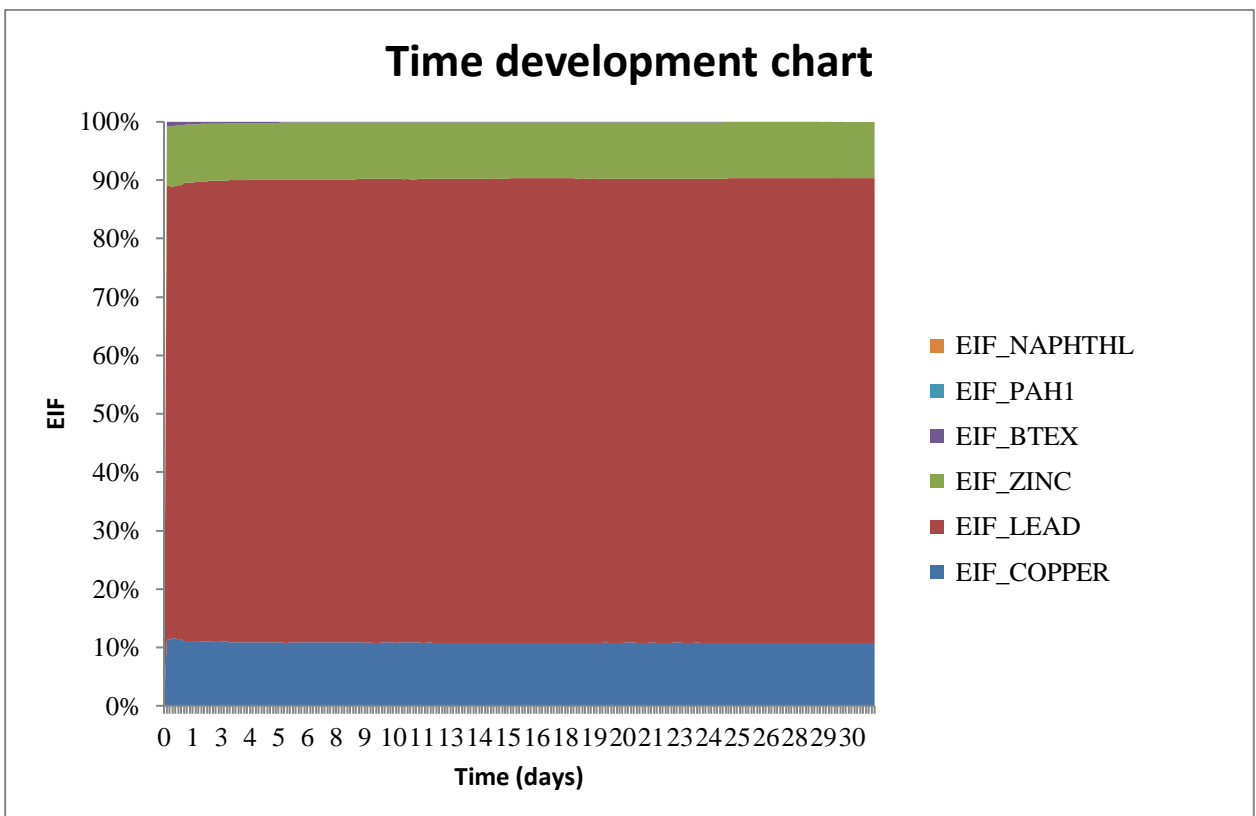
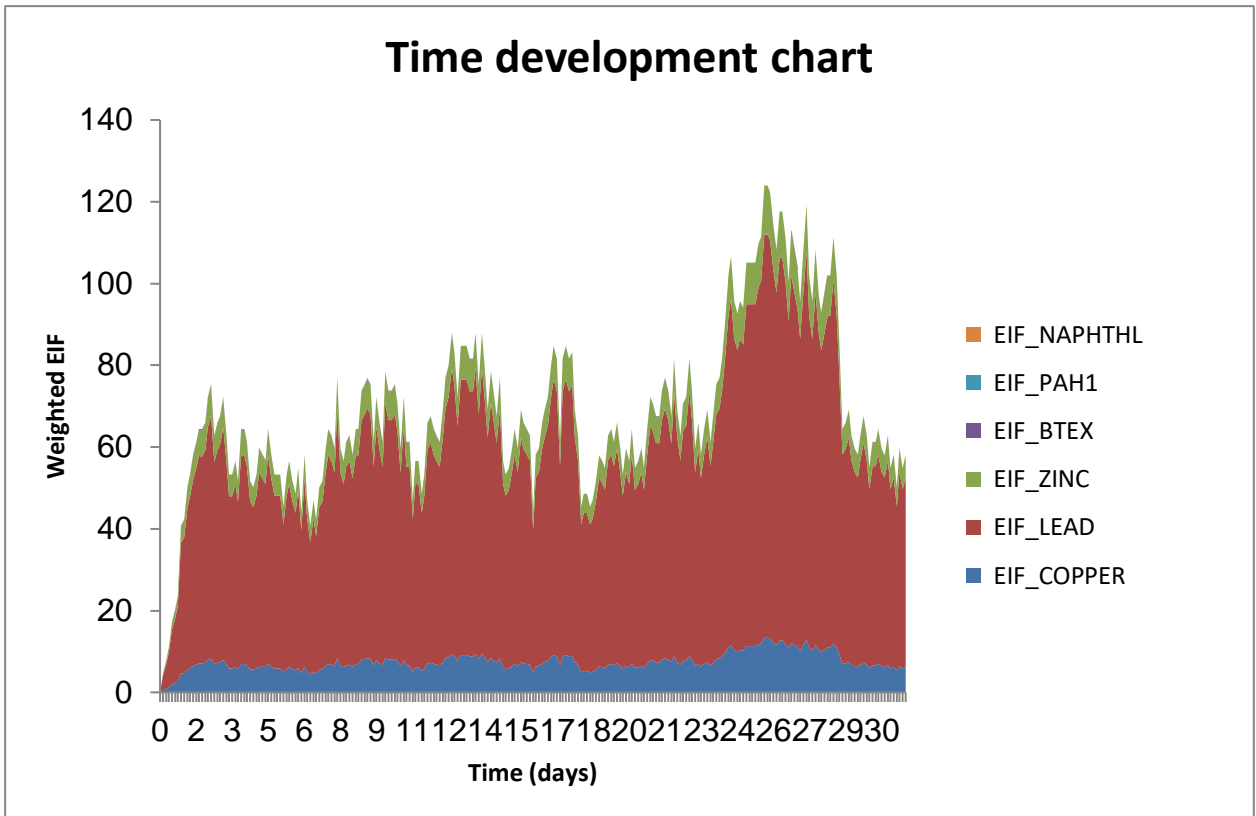


Figure 5.6 Time development chart of weighted EIF and EIF in percentage for 31 days

The mass balance of the contaminants in the water column is shown in Fig. 5.7. According to the mass balance, it can be seen that around 52% of the total mass was biodegraded, and the rest 48% stayed in the water column. It is because of the high initial concentration of BTEX. The initial mixture consisted of BTEX at around the same level of 52%. Since BTEX is not persistent and evaporates quickly from the water, a bit over half of the mixture's mass is removed from the water column. However, the rest of the contaminants are persistent and stayed in the water column.

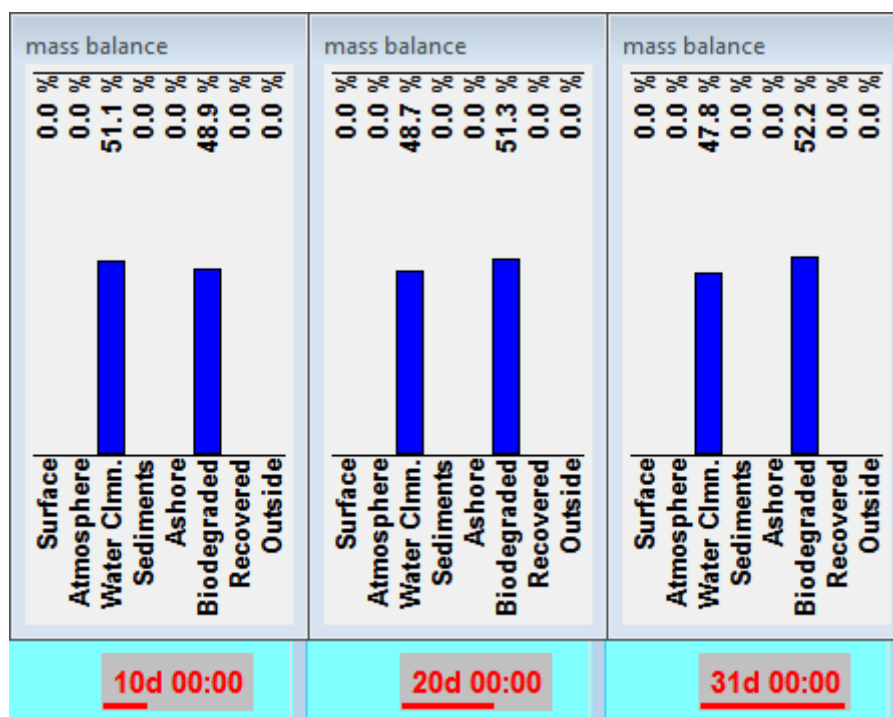


Figure 5.7 Mass balance of the contaminants in the water column in 10, 20, and 31 days

From the time development chart of mass balance, we can observe that in the first days of the simulation, the evaporation rate of BTEX is not that high, but after the 5th day, it was almost entirely evaporated (Fig. 5.8). It shows that in a short-term perspective, the impact of BTEX might be essential, but in a long-term perspective, it does not disturb the marine environment at the most significant level.

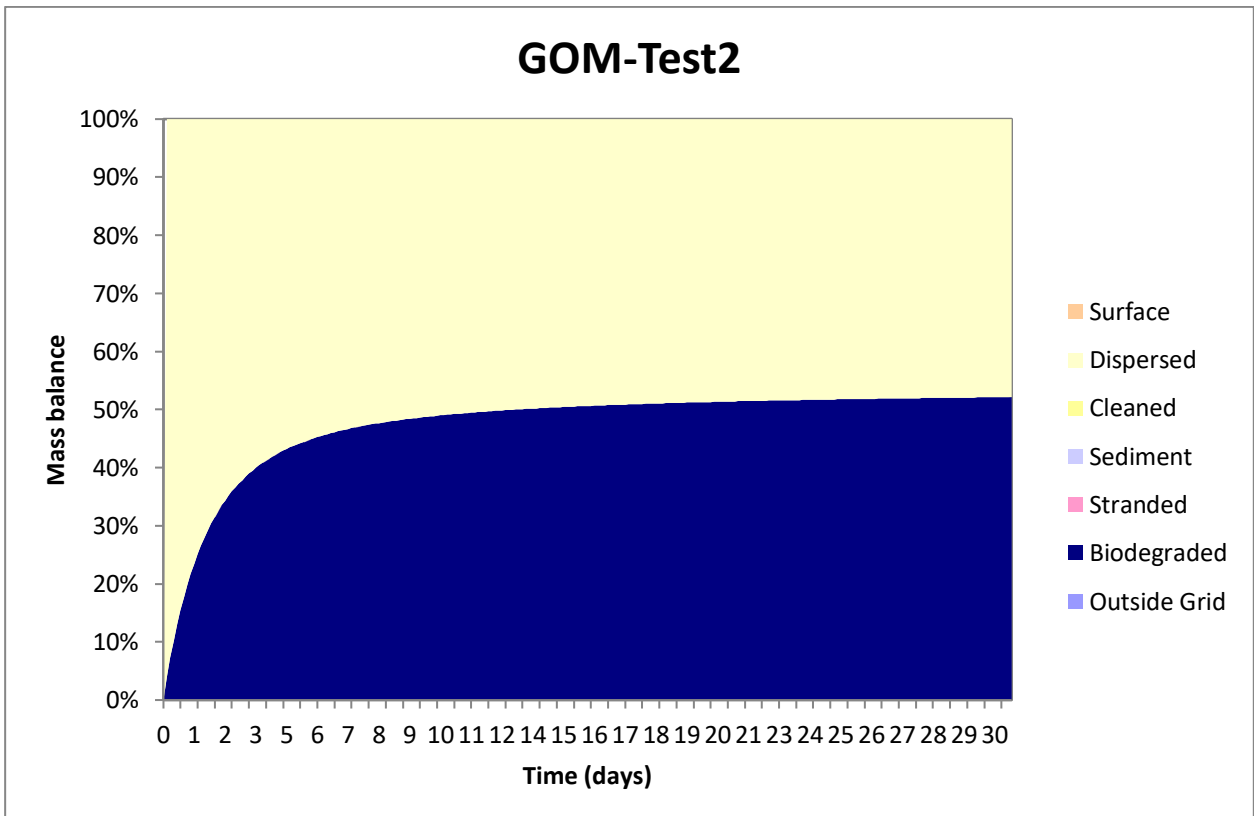
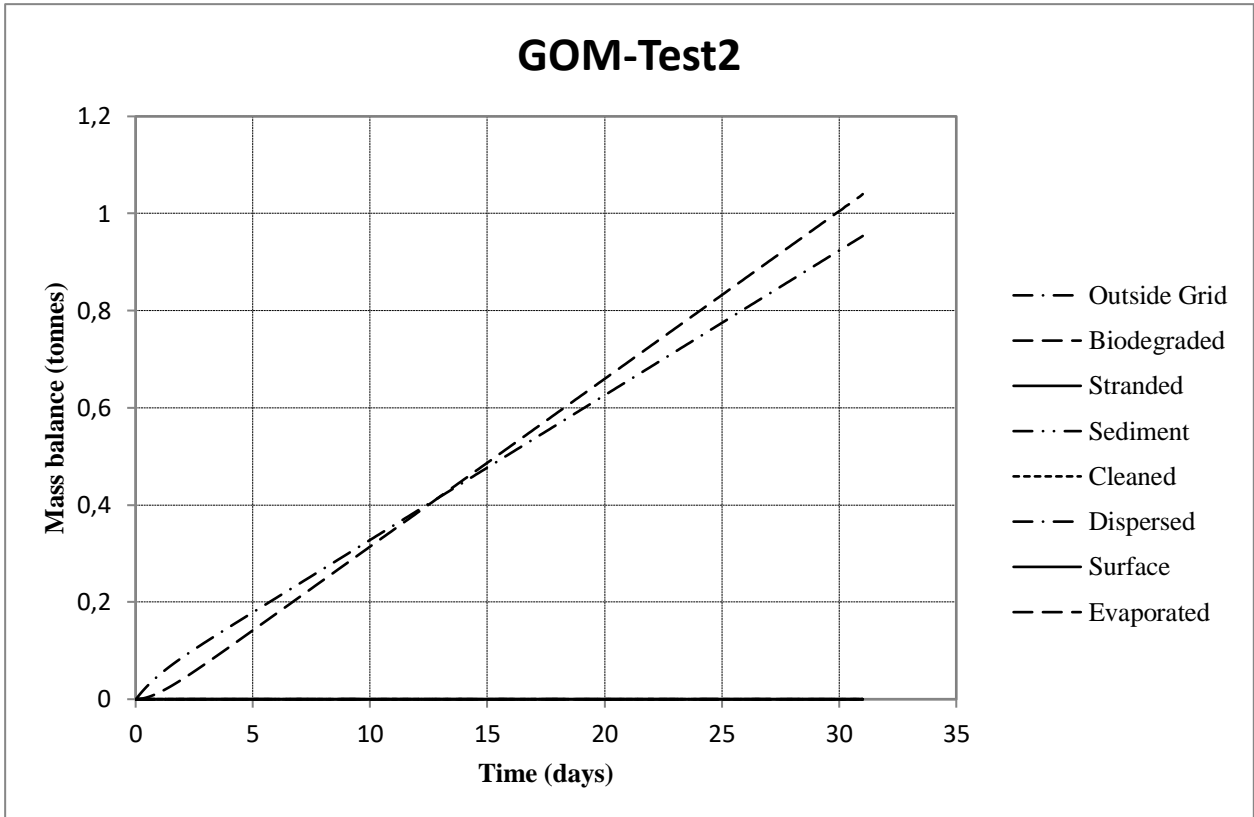


Figure 5.8 Time development chart of mass balance

The obtained risk value before the treatment was 5.35%, and it exceeds the acceptable limit by 1.07 times. This environmental risk value is required for the risk integration of the case

without treatment. Since environmental risk value exceeds the acceptable level, the produced water from the discharge point needs to be treated before releasing it to the marine environment. After applying the treatment methods prosed in the study (EPCON, activated sludge, and sand filters), the risk value was re-estimated as explained in the following section.

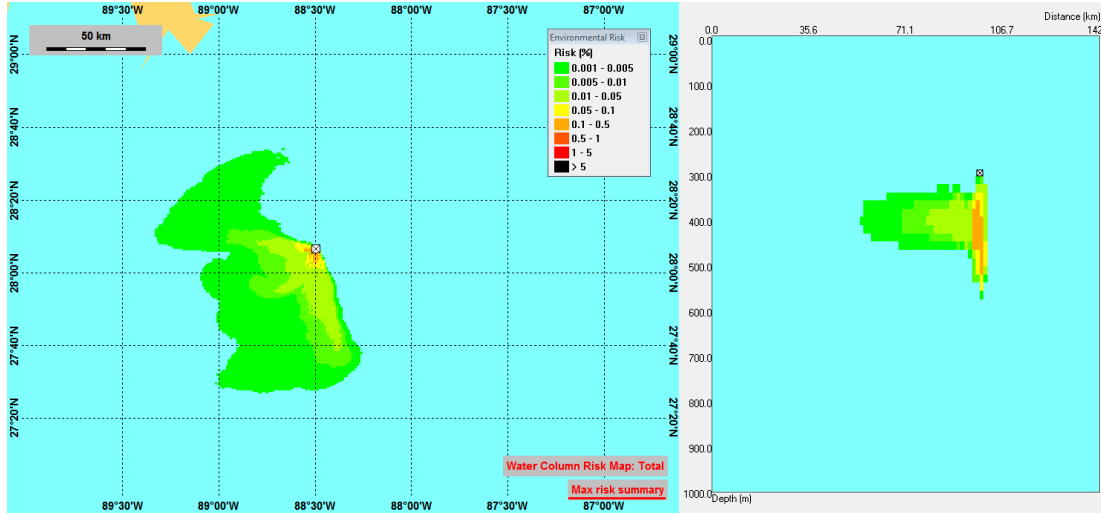


Figure 5.9 Horizontal and vertical Total Risk Map of the simulated discharges after the treatment

The environmental risk after the treatment is 0.43% based on total risk estimation. By taking a ratio of the obtained environmental risk to the acceptable level, the final value of 0.086 can be obtained.

5.2 Technical Risk Assessment

In technical risk assessment of the selected treatment design, the following values were assigned (average numbers of the received responses were considered), as explained in Table 5.1

Table 5.1 Failure Mode and Effects Analysis of the proposed treatment design

Risk factors	EPCON CFU	Activated sludge	Sand filters
Occurrence	4	6	5
Severity	6	4	5
Detectability	3	5	4
RPN	72	120	100

Based on adopting Equation 6, the system’s RPN is:

$$120 \leq x \leq 1000 - \frac{(1000 - 72) \cdot (1000 - 120) \cdot (1000 - 100)}{10^{(3+3-3)}}$$

$$120 \leq x \leq 1000 - \frac{734\,976\,000}{10^6}$$

$$120 \leq x \leq 1000 - 735$$

$$120 \leq x \leq 265$$

We consider the worst-case scenario and take the upper bond of 265, and compare the value with the acceptable level. As a result, the technical risk value for the integration can be obtained, and it is 0.8. In the case of without treatment, since the produced water is being directly discharged from the offshore platform, the RPN is 1 (occurrence is 1, severity is 1, detectability is 1). Hence, the technical risk value for the case of without treatment is 0.003.

5.3 Economic Risk Assessment

To get economic risk value, cost-benefit analysis has to be performed. Jeuland (2015) reports that wastewater collection and treatment (including 3 treatment stages of secondary, activated sludge, and tertiary treatment) cost 2\$/m³. By treating produced water, it is possible to save money that would be spent for a direct discharge without treatment. Additionally, by meeting environmental regulations, it is possible to avoid the fines, which is also a benefit, and the treated water could be used for other purposes, and the marginal cost of water in agriculture is another benefit. The direct discharge would cost 0.05\$/m³, whereas the reuse of water will benefit an extra 0.36\$/m³ (Duraisamy et al., 2013; Haruvy, 1997). Violation of environmental regulation and discharging produced water directly would result in 50,000\$ per day fine. In the case study, 712.5 m³ of produced water (tons were converted into m³ by taking into account the density of 996 kg/m³) is being discharged every day. Therefore, the fine per cubic meter of discharged produced water would be 70.18\$/m³. Taking into account these numbers, the cost-benefit ratio of the treatment design is:

$$\frac{\text{cost}}{\text{benefit}} = \frac{\text{treatment cost}}{\text{discharge cost} + \text{fines} + \text{reuse}} = \frac{2}{0.05 + 70.18 + 0.36} = 0.028$$

In the case of without treatment, the cost part will be discharge cost and fines since the case without treatment does not satisfy environmental regulations; the beneficial part contains the money saved that would be spent for treatment otherwise.

$$\frac{\text{cost}}{\text{benefit}} = \frac{\text{discharge cost} + \text{fines}}{\text{treatment cost}} = \frac{0.05 + 70.18}{2} = 35.115$$

The economic risk value in the case of the selected treatment design is 0.028, whereas without treatment it is 35.115.

5.4 Risk Integration

After calculating environmental, technical, and economic risk values, they have to be integrated into the integrated risk value. In order to do so, experts including regulators, operators, and service providers (engineers) should be surveyed to define the weighting factor of a certain risk contributing to the integrated risk value. In this case study, hypothetical values were assigned in the questionnaire designed to integrate environmental, technical, and economic risks. The results of the questionnaire are:

Table 5.2 The results of the questionnaire designed to integrate risks

Risk	Regulator 1				Regulator 2			
	EnvR	TecR	EcR	<i>Geom.mean</i>	EnvR	TecR	EcR	<i>Geom.mean</i>
EnvR	1	5	3	2.47	1	6	4	2.88
TecR	0.2	1	0.33	0.4	0.17	1	0.33	0.38
EcR	0.33	3	1	1	0.25	3	1	0.9
	Operator 1				Operator 2			
EnvR	1	0.33	0.14	0.36	1	0.33	0.17	0.38
TecR	3	1	0.33	1	3	1	0.33	1
EcR	7	3	1	2.76	6	3	1	2.62
	Service provider 1				Service provider 2			
EnvR	1	0.2	0.33	0.4	1	0.17	0.25	0.35
TecR	5	1	3	2.47	6	1	3	2.62
EcR	3	0.33	1	1	4	0.33	1	1.1

To calculate weighting factors of the matrix, the geometric mean of each risk should be divided by its total, and it results in 63.525% for environmental risk, 9.74% for technical risk, and 23.735% for economic risk based on the regulators' responses (average of two regulators). The results of the operators' responses gave the weighting factors of 9.12% for environmental risk, 24.635% for technical risk, and 66.245% for economic risk (average of two operators). Finally, based on the service providers' responses weighting factors are 9.47%, 64.095%, and 26.435% for environmental, technical, and economic risk respectively (average of two service

providers). At the end in order to get the final weighting factors the average value of all the responses will be taken, and it gives the final weighting factors, which are:

- The weighting factor for the environmental risk: 28.37% or 0.2837
- The weighting factor for the technical risk: 32.82% or 0.3282
- The weighting factor for the economic risk: 38.81% or 0.3881

By applying the weighting factors to the risk values, the integrated risk value in the case of the selected treatment design would be:

$$\text{Integrated risk} = (\text{WF} \cdot \text{EnvR}) + (\text{WF} \cdot \text{TecR}) + (\text{WF} \cdot \text{EcR}) = (0.2837 \cdot 0.086) + (0.3282 \cdot 0.8) + (0.3881 \cdot 0.028) = 0.29$$

Where WF is weighting factor; EnvR represents environmental risk; TecR represents technical risk; and EcR is economic risk

In the case of without treatment, the integrated risk value is:

$$\text{Integrated risk} = (\text{WF} \cdot \text{EnvR}) + (\text{WF} \cdot \text{TecR}) + (\text{WF} \cdot \text{EcR}) = (0.2837 \cdot 1.07) + (0.3282 \cdot 0.003) + (0.3881 \cdot 35.115) = 13.93$$

The integrated risk value in case of without treatment is 13.93, which is far beyond the acceptable level of 1, so the produced water cannot be discharged without any further treatment consideration. In the case of the proposed treatment design, the integrated risk is 0.29, which is below one, and it means that the selected treatment design is a proper alternative that can be applied. The procedures and the results explained in the case study confirm the applicability of the developed framework in managing different alternatives for discharging the produced water into the marine environment. This framework can be also applied as a tool to compare the efficiency of the treatment process of different treatment systems to select the optimum alternative in the specific environmental and operational conditions.

Chapter 6 – Conclusion

Produced water management requires a structured framework that involves multiple aspects and risks associated with it to select a treatment design and justify the decision. To get the full picture regarding the potential risk of produced water management, in this work, environmental, technical, and economic risks are considered in the decision-making process. Minimal work has been conducted on integrated risk assessment of produced water and this study takes the risks into account during the decision-making process. Environmental risk assessment was conducted by using DREAM. This software provides a piechart of the weighted contribution of compounds to the total risk, which gives very useful information. By obtaining this valuable information it is possible to reduce environmental risk by targeting the contaminants which contribute the most to the total risk. A risk-based approach developed in this study can be applied to select and design an effective produced water management strategy. The calculated risks should be compared to the identified acceptable risk level and weighting factors should be assigned based on experts' judgements. It is better to survey all the sides since one side might be mostly interested in decreasing a particular type of risk. For example, regulators are mostly interested in environmental risk, operators in economic, and service providers in technical risk. Getting information from all sides helps to avoid the bias of particular sides. The multiplication of weighting factors to the ratio of calculated-acceptable risk values gives us the final integrated risk value of the treatment or reuse method. The integrated risk can be used as a basis to guide the decision-making process of produced water management. This framework helps to identify the processes that are at higher risks as well as it shows the areas which need to be improved in order to mitigate the integrated risk. Summary of highlights of the research:

- Developed an integrated framework for risk-based management of produced water;
- Developed an approach for assessing integrated risk associated with produced water treatment and reuse;
- Modeled transport and fate of primary pollutants in produced water;
- Performed risk assessment of produced water treatment and reuses processes;
- Calculated cost-benefits analysis of produced water treatment and reuse processes;

- Integrated environmental, technical, and economic risks to support decision-making of produced water management;
- Demonstrated the application of the risk-based approach through Thunder Horse Oil Field study.

Future work will be devoted to further developing more advanced methods for assessment of environmental, technical, and economic risks of produced water treatment strategies. For example, future work may investigate a) how to handle the uncertainties in the risk-based approach, b) the opportunity of incorporating optimization models in the risk-based approach.

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