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Abstract

The global interest in exploiting deep-sea minerals has increased over the last couple of decades due to the rising demand for valuable metals required for technological development. However, due to significant scientific and technological knowledge gaps and uncertain economic risks, no commercial exploitation of deep-sea resources has yet been initiated (Jak et al., 2014). To help develop appropriate environmental management and monitoring plans and to assist in establishing necessary standards and guidelines for future environmental impact assessments, this thesis provides a comprehensive list of potential hazards of seafloor-massive-sulfide mining with risk-related and other environmental management factors. It also includes evaluations of the importance and priority of the hazards for inclusion in the ecological risk framework. From the list of identified hazards, the essential ones were further elaborated in terms of consequences for the marine environment. The rest of the hazards were grouped into scale-dependent and knowledge-dependent for future evaluations of importance, relevance, and priority. It is, at present, difficult to predict the relevance and importance of scale-dependent and knowledge-dependent hazards. Once more knowledge about the physical effects of particles and their ecological and toxicological effects is gathered, the decision of whether these hazards should be included in the environmental risk assessment framework may be made.

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Table of contents

List of abbreviations

CTD	Coastal shallow-water disposal
DISCOL	Disturbance and Recolonization Experiment
DSM	Deep-sea mining
DSTP	Deep-sea tailing placement
EBM	Ecosystem-based management
EIA	Environmental Impact Assessment
ERA	Environmental Risk Assessment
FAO	The Food and Agriculture Organization
ISA	International Seabed Authority
LC_{50}	Lethal concentration where 50% of organisms are affected
LD_{50}	Lethal dose where 50% of organisms are affected
NC	Natural Capital
NPI	Net Positive Impact
OSPAR	Oslo and Paris Commission
PEC	Predicted Environmental Concentration
PNEC	Predicted No-Effect Concentration
SMS	Seafloor massive sulfides
SOFAR channel	Sound Fixing and Ranging channel
STD	Submarine tailings disposal

1 Introduction

The seafloor of the world's oceans is rich in marine minerals such as manganese nodules, Co-rich ferromanganese crusts, seafloor massive sulfide (SMS) deposits, and some rare earth metals (Petersen et al., 2016). The SMS deposits are leached metals that precipitate on the seafloor when hot earth fluids (up to 350 °C) rise through the thermal vents and are usually found at water depths varying from 350 to 5000 metres (Figure 1). These deposits contain copper, zinc, cobalt, nickel, silver, and gold, which are used in diverse industrial applications and are also needed to develop low carbon technologies for the global transition to a zero-emission society (Collins et al., 2013; Miller et al., 2018; Teske et al., 2016).

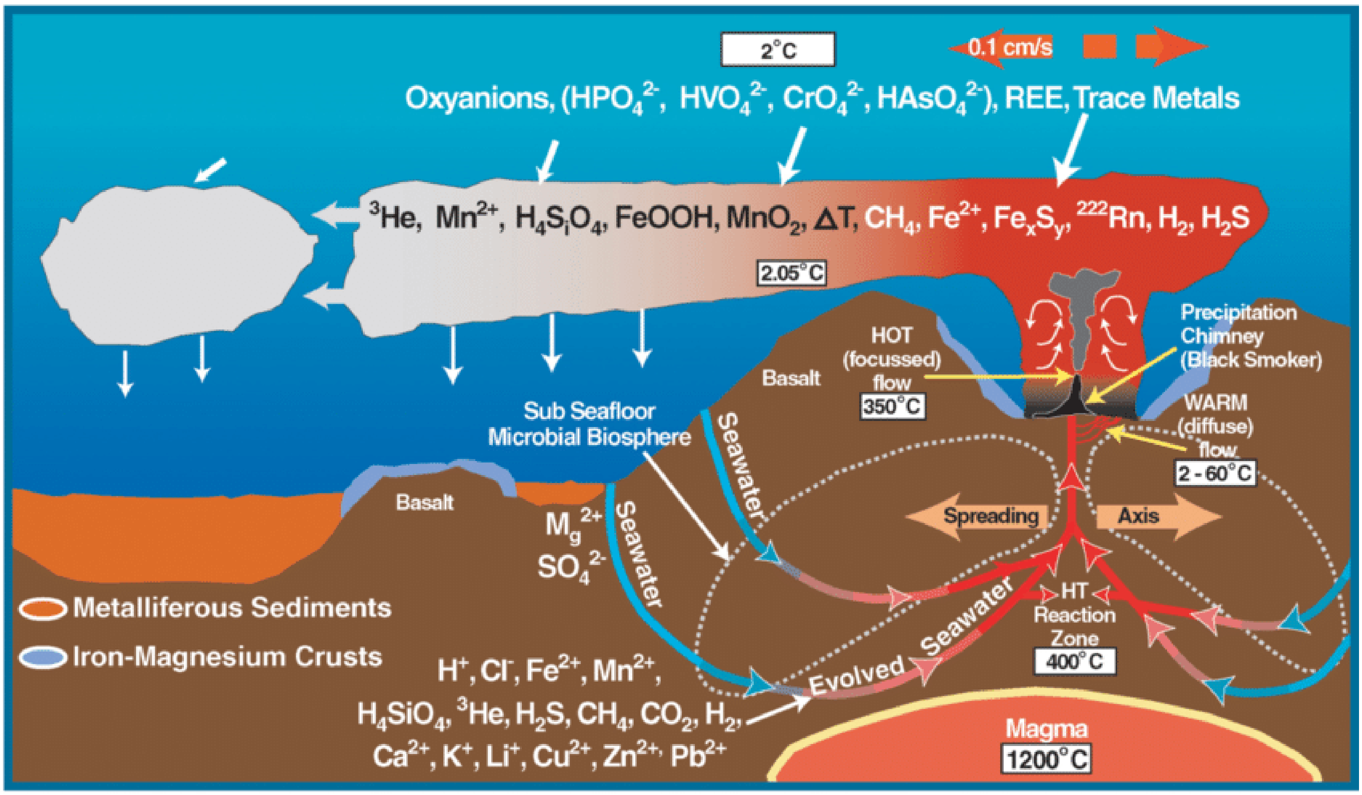

Figure 1. Schematic diagram of a hydrothermal vent system. Volcanic heat at the mid-ocean ridge axis drives hydrothermal circulation and chemical exchange between the ocean crust and seawater. A mid-ocean ridge hydrothermal system, plume, and resulting deposits and precipitates are featured. From «Environmental Impacts of Nodule, Crust and Sulphide Mining: An Overview» by Weaver and Billet, 2019, p. 3. Copyright 2019, Springer Nature Switzerland AG.

At present, metals are mostly mined from ore deposits on land. However, these are becoming more difficult to find, more expensive to extract, and come with higher risks and environmental footprint. Excavation of these deposits creates vast amounts of waste and tailings to recover only a tiny amount of metal (Lempriere, 2017). At the same time, the global demand for metals is rising as the world's population is expected to reach 9.7 billion by 2050. This issue drives the mining industry to explore alternative sites for mineral mining, namely, the seabed, where mining might have significant environmental impacts (Petersen et al., 2016). Deep-sea mining (DSM) is promoted by some companies and governments as a reasonable and environmentally viable alternative to terrestrial mining due to the mineral demand, particularly for the technology development required to reduce global carbon emissions

(Chin & Hari, 2020; Lempriere, 2017). The dilemma of mining activity with a potential environmental impact to achieve «the green shift» is also widely discussed among researchers. Some argue that there is a need for mining activity in the deep sea to manage the transition to green energy (Batker & Schmidt, 2015), while others state that there is no necessity for DSM on the path towards renewable energy and to combat climate change (Stabell, 2021; Teske et al., 2016). The most important aspect of this issue is how big the ecological footprint DSM might cause, and to what extent can the industrial actors mitigate it?

1.1 Background of deep-sea mining

The existence of mineral deposits in the deep sea has been known for decades. However, the interest in the exploitation of these deposits has increased in recent years mainly due to the rising demand for valuable metals such as cobalt and nickel, as well as rare earth metals needed for the development of advanced technologies. Because of technological difficulties, knowledge gaps, and uncertain economic risks, no commercial exploitation of DSM resources has yet been conducted (Jak et al., 2014).

Impacts from the mining of SMS deposits (Figure 2) are predicted to vary from direct removal of habitats to indirect harmful effects on the surrounding benthic and pelagic communities. The latter might be caused by toxic and particle-rich sediment plumes, contaminant release, and other impacts generated by the mining gear, such as increased noise, light, vibration, and temperature (Boschen et al., 2013; Miller et al., 2018; Van Dover, 2014). These risk sources may disrupt population connectivity and lead to loss of ecosystem functions and species extinction (Van Dover, 2014). Population connectivity is an essential topic in marine ecology, encompassing the exchange of individuals among geographically separated subpopulations that comprise a metapopulation (Cowen & Sponaugle, 2009). The subject is vital for understanding the resilience of biological communities to the impacts of seabed mining and the conservation of biodiversity through environmental management planning. A good ecological management strategy is crucial for ecologically sustainable mining activity in the ocean. However, due to knowledge gaps and uncertainties associated with SMS mining, it is a real challenge to predict the severity of environmental impacts and our ability to mitigate them (Van Dover, 2014). To detect possible future changes caused by mining activity, minimize ecological footprint, and develop a responsible seabed mining industry, comprehensive surveys and studies on benthic habitats of potential mining sites and surrounding areas must be conducted (Clark et al., 2020). Such studies will provide scientific data that will advance our knowledge in important topics such as community ecology, evolution, and adaptation to extreme environments and contribute to developing tools and methods for the sustainable development of seabed mineral mining (Moodley, 2020).

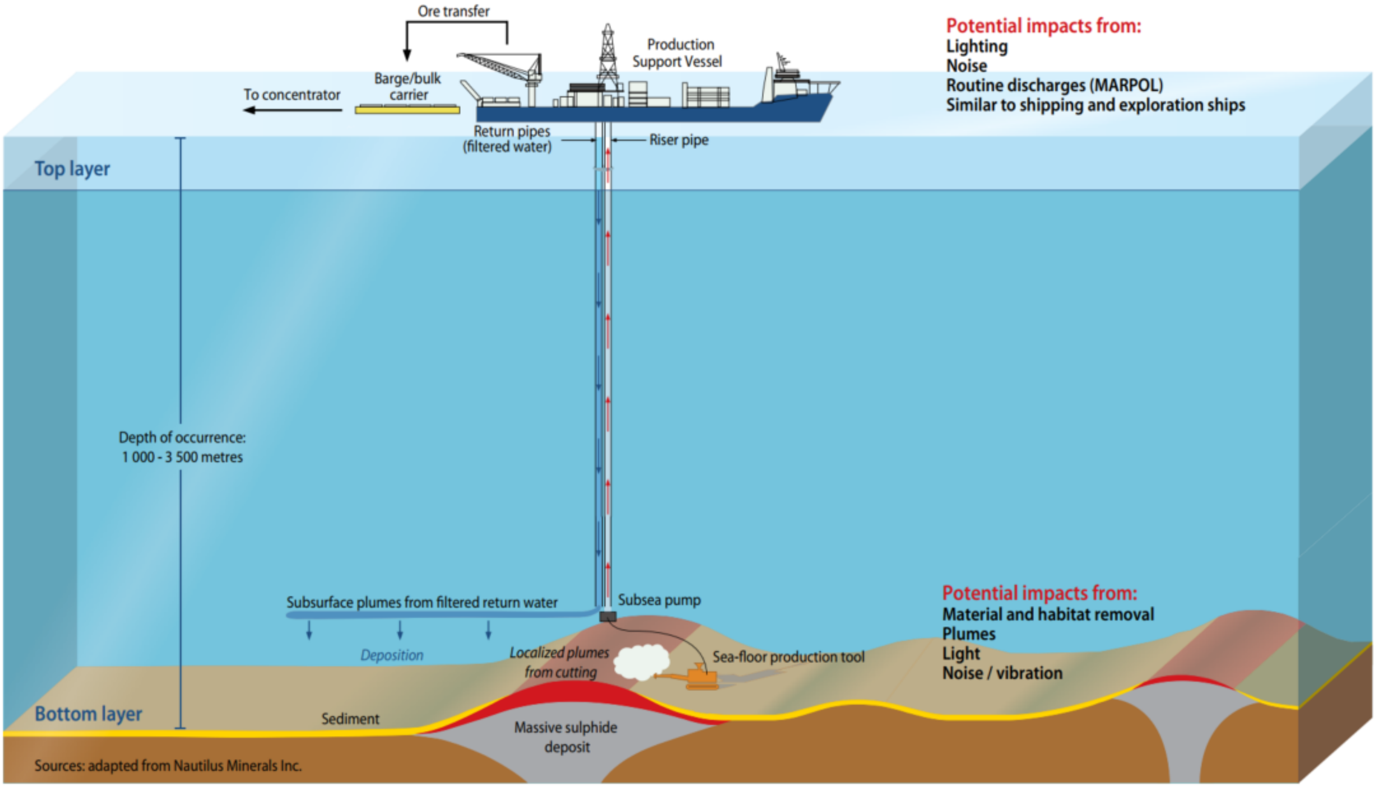

Figure 2. Example of an SMS mining system and related sources of potential environmental impact. From «Seafloor massive sulphides: A physical, biological, environmental, and technical review» by Clark et al., 2013, p. 37. Copyright 2013, Secretariat of the Pacific Community (SPC). The sketch is probably not representative of the excavation technology currently being developed (W. Sognnes & S. Sanni personal communication, 29 May 2022).

1.1.1 The DSM cycle

The DSM cycle encompasses three types of operations: prospecting, exploration and exploitation (Figure 3). The current focus of DSM is aimed at prospecting and exploration, where the extraction, transport and surface operation techniques needed for exploitation are developed and tested on a small scale.

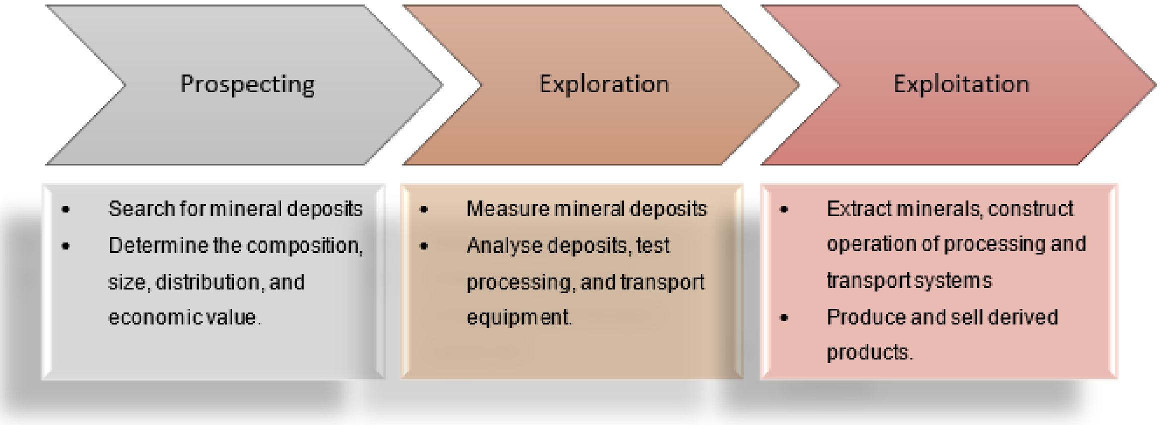

Figure 3. Operations in DSM cycle: prospecting, exploration and exploitation (Inspire by World Bank, 2017, p. 26).

In the prospecting phase, a variety of techniques are used to search for and map the areas of mineral deposits within the designated license areas in international waters or within a nation's exclusive economic zone. The aim is to locate mineral deposits and determine their composition, size and distribution, as well as their potential economic value. Further, the exploration phase covers the measurement of deposits in grade and tonnage, as well as testing of the mining, transport and process equipment. The information from technical, social, economic, and environmental studies should be provided in this phase for upscaling to commercial mining. The last phase, the exploitation, encompasses commercial mining activities, which include mineral extraction, construction and operation of processing and transport systems to produce and sell minerals and derived mineral products (Chin & Hari, 2020; World Bank, 2017).

1.1.2 Earlier approaches to DSM

Ahnert & Borowski (2000) presented in their paper an overview of the precautionary research studies which previously were pursued in advance of the environmental impact of DSM. The first early approach of ERA for DSM was connected to the pre-pilot mining tests, where prototypes of mining devices for metalliferous mud mining and manganese nodule mining were used. The ERA associated with the Deep Metalliferous Sediment Development Programme in the Red Sea (MESEDA, the late 1970s) was conducted from 1977 to 1981 and mainly addressed the toxicity and composition of discharged tailings, its hydraulics and plume development, as well as their effects on environment and organisms. The study comprised oceanography of the seabed and water column, the ecological assessment of pelagic and benthic communities, and studies of heavy metals in water, hot brines, sediment, and animals. During another study in the Pacific Ocean, the Deep Ocean Mining Environmental Study (DOMES), small quantities of manganese nodules were brought to the surface by prototype collector sledges. Short-term effects of tailings discharge were investigated on biota at the surface and in the water column, and effects on benthos induced by the collector system and by the created benthic plume were examined. Both these programmes have contributed with data and knowledge of the marine environment, which led to the development of a new approach to precautionary impact assessment. However, the environmental scientists concluded that environmental impact studies on a larger scale are necessary for the extrapolation to full-scale mining (Ahnert & Borowski, 2000; Thiel, 1991).

The first large-scale *in situ* disturbance experiment (at approximately 4150 m depth), which allowed for long-term monitoring of the disturbed benthic community, was initiated as a part of a DISCOL programme (Disturbance and Recolonization Experiment). A physical disturbance similar to an expected seabed impact during manganese nodule mining operations was created by a specially designed disturber device resulting in mortality of the organisms in the disturbing tracks, elimination of hard substrate habitat, the burial of fauna by overturning sediment, suspension of near-surface fauna and blanketing of fauna in the near field by redeposition of the suspended benthic plume. The program operated seven years after the disturbance, and the research focused on short-term impacts on the benthic biota, repopulation of the disturber tracks, and community recovery. The ecological and taxonomic tests concentrated on organism groups with considerable abundances: *Nematoda, Foraminifera, Holothurioidea, Polychaeta* and *Harpacticoidea*. The DISCOL results indicated that for most benthic organisms, the repopulation of the tracks was accomplished by lateral migration of adults rather than larval settlement from the water column, as predicted earlier from small-scale colonization experiments. Moreover, no opportunistic behaviour of a single species exploiting the free habitat resources was discovered in contrast to previous experiments with organically enriched sediments (Snelgrove et al., 1994). These findings indicated that there is an essential difference between the effects of physical disturbance of the sediment and organic enrichment in the deep-sea environments (Ahnert & Borowski, 2000). A series of *in situ* experiments were also conducted to investigate environmental effects due to plume generation in the benthic impact experiments. A disturber device was used to fluidize bottom sediments, which were later lifted to a height of 5 m and dispersed by near-bottom currents. The environmental impact on the benthic community was assessed by faunal analyses using sediment samples and photographic material. A decreased abundance of nematodes in the sediment redeposition zones was reported, but no negative effects on harpacticoid copepods were observed. Macrofaunal families *Polychaeta* and *Isopoda* showed increased abundance in disturbed areas and were considered promising candidates for monitoring mining-related impacts on the deep-sea environment (Ahnert & Borowski, 2000; Trueblood et al., 1997).

Ahnert & Borowski (2000) suggested that considering that the human activity in the deep-sea is predicted to impose severe and long-lasting impacts, a precautionary principle should be applied, and the ERA should rely on *in situ* experiments starting with a small-scale impact simulation and proceeding stepwise to the full-scale monitoring followed by thorough evaluation at each step.

1.2 Precautionary principle

A precautionary principle is an approach that emphasizes caution in innovative projects with the potential for causing harm when thorough scientific knowledge is deficient (Read & O'Riordan, 2017). It requires addressing and preventing environmental risks at an early stage, including the identification of knowledge gaps and uncertainties, to ensure these can be addressed and taken into account in a robust decision-making process (Durden et al., 2018; Jaeckel et al., 2017). The United Nations (UN) proclaims: «In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation» (United Nations, 1992). This is particularly important in the context of DSM due to the insufficiency of standardized environmental data from areas targeted by the industry and especially relevant for hydrothermal vent and seamount ecosystems in the study area. DSM has a risk of causing irreversible damage to the environment - more information is required to understand the ecotoxicology and potential bioaccumulation of metals released at different depths and to determine how nutrient enrichment will affect pelagic food webs (Chin & Hari, 2020).

1.3 Laws and regulations

Given that many of the zones rich in seafloor minerals lie outside of national jurisdictions, coordination and management of DSM in these areas fall to a multilateral body – The International Seabed Authority (ISA). It was established by UN Convention on the Law of the Sea (UNCLOS) to manage and regulate DSM at the seabed in areas beyond national jurisdiction. It comprises rules, procedures, and recommendations that in recent years have addressed the principle of ecosystem-based management (EBM) and require adequate protection of the marine environment from the harmful effects of DSM. ISA is responsible for regulating and controlling current exploration activities, as well as future mining activities, in the Area for the benefit of humankind as a whole. ISA's mandate lies in its duty to take all necessary measures to ensure effective protection of the marine environment from harmful effects which may arise from seabed activities. It follows that the ISA is required to adopt appropriate rules, regulations and procedures for the prevention, reduction, and control of pollution and other hazards to the marine environment; the protection and conservation of the natural resources of the Area; and the prevention of damage to flora and fauna of the marine environment (Niner et al., 2018; United Nations, 1982, art. 145). In the recommendations, ISA points to the need for extensive baseline studies before the areas are opened up for mineral activities, as well as the need for pristine and representative reference areas that will not be exposed to influences from mineral extraction in the seabed (ISA, 2013).

1.4 Industrial management

A regulatory risk management framework needs to integrate the assessment of environmental effects and impacts with an assessment of the environmental standards and measures to reduce the risks while considering the scientific, management, and operational uncertainties (Cormier & Londsdale, 2020; ISA, 2013). While the authorities must assess environmental consequences in the management context, the executing industry must ensure good environmental management. Environmental management should be based on environmental risk analyses. A suggested framework for environmental assessment and management is illustrated in Figure 4.

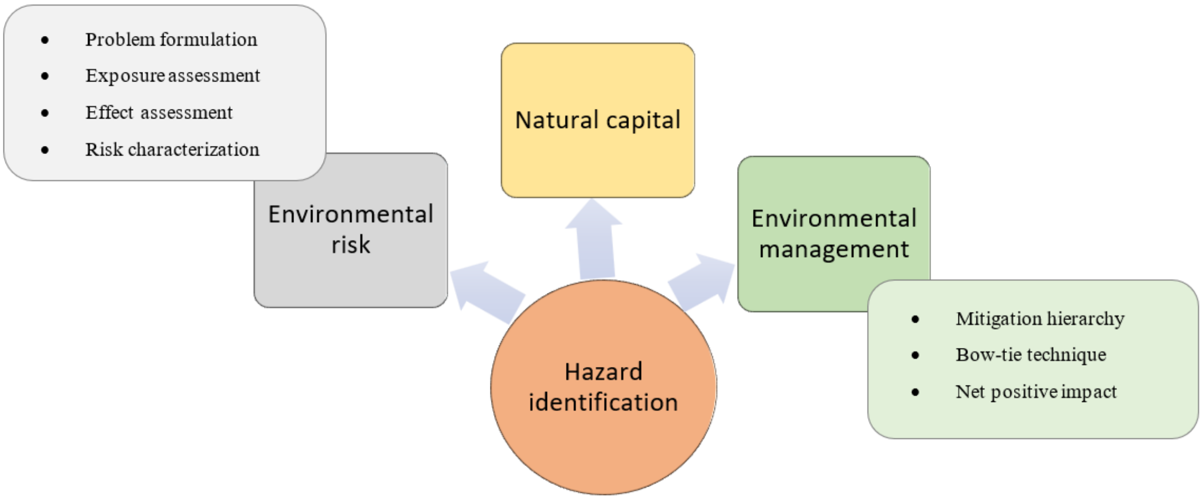

Figure 4. An overall framework for environmental risk assessment and management elaborated on in this thesis.

1.5 Objective and scope of the thesis

This thesis project aims to provide a base for the environmental risk assessment framework for future environmental studies and management aspects of DSM projects. Since there are three types of deep-sea mineral deposits: polymetallic nodules, ferromanganese crusts, and massive seafloor sulfides, and the potential environmental impacts are likely to differ between different sources, the scope of this project is limited to SMS deposits, being the mining type of highest current interest for Norway.

So far, the compilation of potential hazards is too deficient for the establishment of an ecological risk framework for future ridge mining activities. The main objective of this thesis is, namely, to identify and assemble a list of potential hazards of SMS deposit mining with associated consequences, exposure measures, effects on biota, and other environmental management factors, as a base for the development of ecological risk assessment framework to inform risk-based environmental management. Secondary objectives are to discuss initial considerations of the identified hazards in terms of importance and priority for inclusion in the ecological risk framework and to present a list of additional aspects of environmental management that may provide tools for decision-makers to conclude if and how the mining activities should be carried out. This will assist in developing appropriate environmental management and monitoring plans and help set crucial standards and guidelines for future environmental impact assessments (EIA).

2 Methodology

This thesis is a desktop study solely based on information gathered from the available literature and information provided by the stakeholders in the industry and university. The work does not include any laboratory/fieldwork or use of experimental data. The literature on this topic is limited, and some information, such as conceptual designs of mining technology, is currently confidential. Therefore, the method has been to search for the publicly available literature, from scientific peer-reviewed journals to reports and other public documents, including consequence programme hearing statements from different industrial actors to the Norwegian Government and ISA reports. Information from a total of 67 sources was assimilated and assembled to reach the objectives stated in section 1.5.

3 Theory

The following sections present the results of a literature review made on the topic. It includes a description of the environmental management framework and its significance for mining SMS deposits, an explanation of ERA and its component parts, and findings on additional aspects of environmental management: EBM, risk management strategies, NPI and NC.

3.1 Environmental management framework

The purpose of environmental management is to minimize environmental degradation caused by humans by maximizing the benefits of resource utilization. It involves describing and monitoring expected or actual environmental changes to enable good decisions to be made in order to reduce impacts. However, the management of the environmental effects related to DSM is complex – it involves various topics such as sediment characteristics and geochemistry, particle sinking velocities and aggregation, hydrodynamic plume modelling, noise and light hazards, toxic discharges, chemical contamination, marine biology and biodiversity from the sea surface to the seabed, genetic connectivity, as well as the value of ecosystem functioning and services. There is a wide range of tools for environmental management, but for DSM specifically, an ERA process is required as a part of the EIA (Weaver et al., 2018). For an ERA framework relevant to ridge mining activities, the potential risk factors must be identified, and the risk must be characterized based on exposure to identified stressors and resulting ecological and toxicological effects. Most of the information required for such work is generated through laboratory experiments. However, the ecological relevance should also be validated in the field by *in situ* experiments to identify indirect risk factors associated with the mining operations (Moodley, 2020). Based on the ERA, the ISA or Norwegian authorities can decide if a project can go ahead, and on the critical risks to the environment, how the impacts of the project should be reduced (Weaver et al., 2018).

3.2 Environmental risk assessment

The environmental risk assessment (ERA) is a method within a risk management context for identifying and assessing undesirable human-induced changes to the environment (US Environmental Protection Agency (US-EPA), 1998). Various ERA frameworks for different application areas are available in the literature (Vora et al., 2021), and in the present thesis, no discrimination is made between environmental and ecological risk assessment. Generic ERA framework covers identifying a potential problem, followed by exposure and effect assessments, which provide the base for risk characterization. Figure 5 represents the four main phases of risk assessment (enclosed in the red box) and other critical steps in risk management (US Environmental Protection Agency (US-EPA), 1998). Even though risk assessment and risk management are distinct processes, the discussions between the assessor and manager are essential to ensure that the assessment will address all relevant ecological concerns and provide pertinent information for decision-making. Effective communication also contributes to understanding the assessment's assumptions, conclusions, and limitations (Norton et al., 1992).

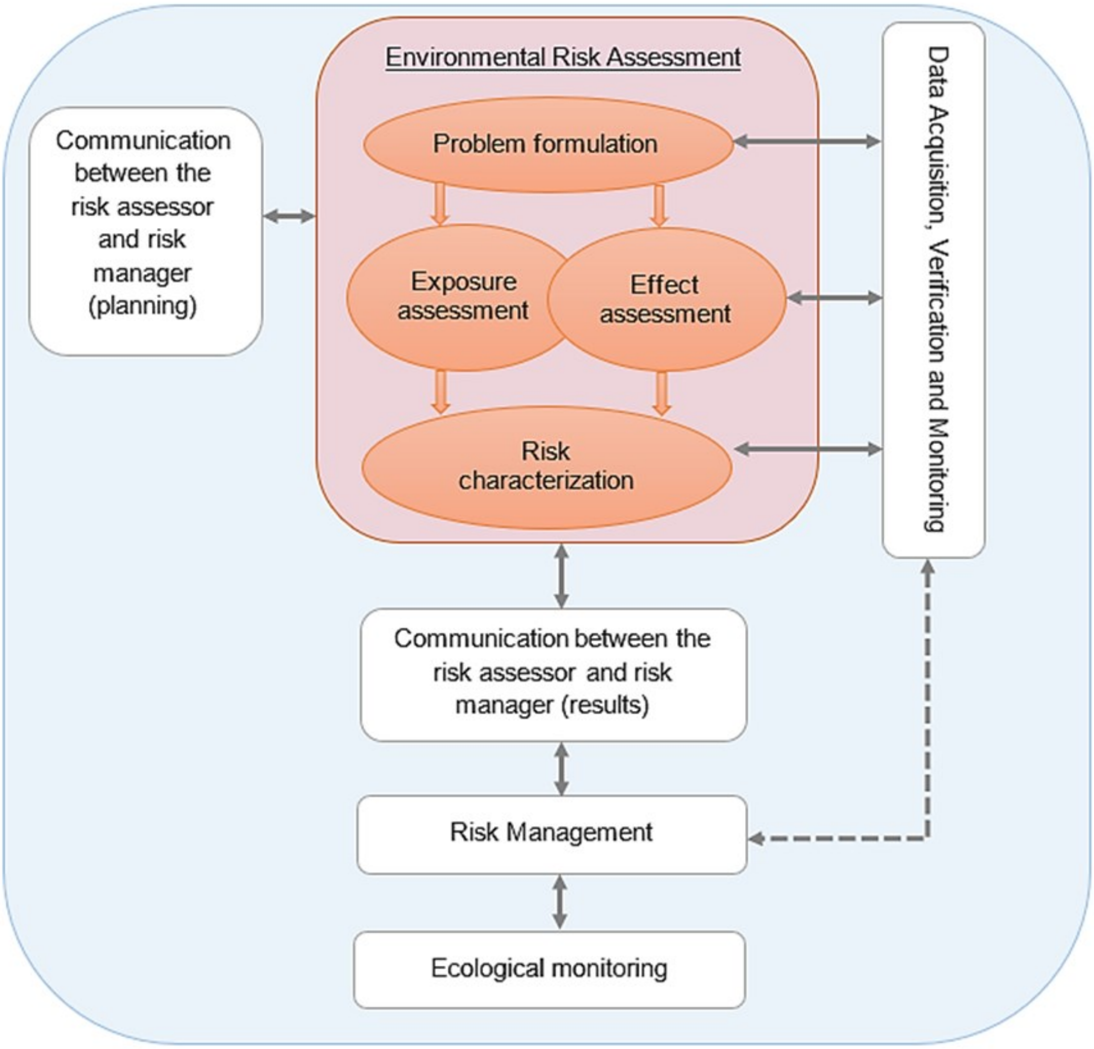

Figure 5. Environmental risk assessment framework (Inspired by U.S. EPA, 1998).

To estimate the potential harm of stressors, the dose-response tests are usually carried out on ecologically relevant species (common species). The dose-response curves obtained from these tests describe the change in effect on an organism caused by differing levels of exposure to a stressor (Figure 6). Mortality is commonly chosen as a study endpoint, and the lethal dose (LD50) or lethal concentration (LC50) required to kill 50% of the population is often determined. If the effect is achieved by low chemical concentration, the chemical is said to have a high potential to cause harm (Calow, 1998; Walker et al., 2012, p. 98).

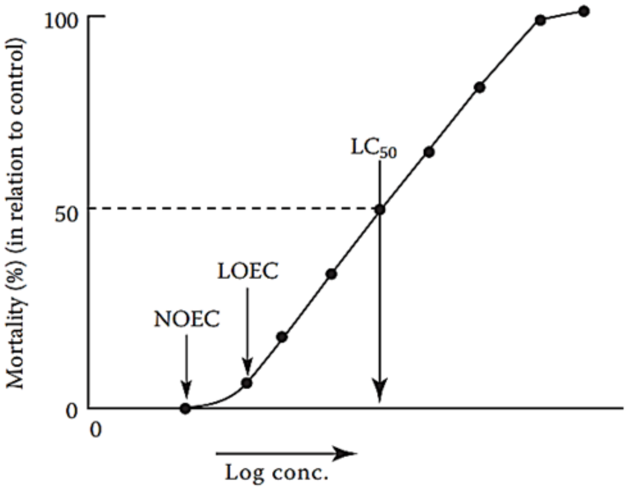

Figure 6. Dose-response curve showing NOEC (no-observed-effect concentration), LOEC (lowest-observed-effect concentration), and LC50 (median lethal concentration) values. From «Principles of ecotoxicology» by Walker et al., 2012, 4th ed., p. 98. Copyright 2012, Taylor & Francis Group, LLC.

3.2.1 Hazard identification

Problem formulation is a crucial step of any ERA process – it provides a foundation for the entire risk assessment. It involves stating the purpose and developing a plan to analyse and characterise risk. This step generates conceptual models and assessment endpoints by integrating combined information on risk sources, stressors, effects, and ecosystem characteristics. The conceptual models and assessment endpoints are necessary for the final product of problem formulation, i.e., a plan for the analysis and characterization of risk (US Environmental Protection Agency (US-EPA), 1998).

3.2.2 Exposure assessment

In exposure assessment, data is evaluated to describe stressor sources, their distribution in the environment, the magnitude of exposure, and their behaviour and fate in the environment (US Environmental Protection Agency (US-EPA), 1998; Vora et al., 2021). The aim is to determine the potential environmental concentration (PEC) factor, estimated by the physical spreading, biodegradation values, and bioaccumulation potential of the stressor (Smit et al., 2006). These parameters reflect the fate of the chemical and its potential for degradation and accumulation in the receptor organisms. The temporal and spatial stressor distribution must be compatible with the ecological region for the appropriate exposure estimation. Typically, the data may not be available for all aspects of the analysis. If so, the assessor will need to make assumptions with varying degrees of uncertainty, which later are summarised during risk characterization. The output of this analysis is a summary profile of exposure, which is used in the risk characterization phase together with the effect assessment profile (Norton et al., 1992).

3.2.3 Effect assessment

In effect assessment, the response of a receptor to a particular stressor is analysed to make a stressor-response profile (Figure 6). The aim is to derive a predicted no-effect concentration (PNEC) factor for the stressor, defined as a threshold concentration of harmful effects for a group of receptor organisms. The PNEC value is commonly determined by dividing the toxicity test results, i.e., LC_{50} values, by an arbitrary assessment factor. Depending on the toxicity test data available for different species and whether the toxicity data is for short-/long-term exposure, the value of the assessment factor changes. Toxicity tests encompass the effect of the chemical at different concentrations on the receptor organism or its tissue (Vora et al., 2021). As for the exposure assessment, uncertainty is essential for evaluating the relationship between stressor levels and ecological effects (US Environmental Protection Agency (US-EPA), 1998).

3.2.4 Risk characterization

Risk characterization is based on the exposure and effect profiles and is the final phase of ERA. Risk assessors evaluate ecological risks during this phase, specify the overall degree of confidence in the risk estimates, present evidence supporting the forecast, and interpret the unfavourable environmental effects (US Environmental Protection Agency (US-EPA), 1998). The PEC and PNEC values are compared. If PEC: PNEC ratio is <1, it is anticipated that the probability of adverse effects is low and that there is no need for further testing or risk reduction (Calow, 1998). Risk characterization also integrates the strengths and limitations of the previous analyses and accounts for the assumptions and scientific uncertainties made during the assessment. Risk managers make their risk handling decisions based on the risk assessment results, along with other factors, such as economic or legal concerns. They also rely on the risk assessment results when communicating risk to the stakeholders, including authorities and the general public. Therefore, the results, major assumptions, uncertainties, and scientific conclusions must be expressed clearly in the risk characterization report to guarantee mutual understanding between risk assessors and managers (US Environmental Protection Agency (US-EPA), 1998).

3.3 Additional aspects of environmental management

At present, our knowledge of deep-sea ecosystems is generally limited and fragmented. Knowledge gaps in deep-sea ecology and topics such as community ecology, evolution, and adaptation to extreme environments prevent the industry from proceeding with deep-sea mineral extraction. Specific ridge mining features must be obtained and implemented into a general ecological risk assessment framework for potential future mining activities in the world's oceans. As the ridge mining-specific features for such a framework are at present undefined, the industry expresses a need for additional terms and tools to advance the knowledge in topics such as EBM, the mitigation hierarchy, NPI, and NC to be clarified.

Such topics are addressed by industry and finance initiatives like the “world business council for sustainable development” and “taskforce on nature-related financial disclosures” (A. Myhrvold personal communication, January 2022). It is reasonable to think that these may contribute to providing knowledge and tools for decision-makers to conclude whether the mining activities should be carried out and, if so, to develop appropriate environmental management and monitoring plans and help set standards and guidelines for future EIA.

3.3.1 Ecosystem-based management/ Ecosystem services

DSM may inflict significant (and potentially irreversible) damage to various deep-sea habitats and ecosystems and result in the loss of biodiversity. The adverse effects may originate from the formation of sediment plumes and seawater contamination during the extraction of metallic resources or from noise, vibration, and light emitted by the mining gear (Guilhon et al., 2021; Miller et al., 2018). The greatest challenge in securing sustainable utilization of deep-sea minerals is ensuring the effective protection of the natural environment. As part of environmental management solutions, more comprehensive approaches such as EBM should be adopted to ensure the sustainable development of DSM (Guilhon et al., 2021). While there is no clear definition for EBM, The UN Convention on Biological Diversity describes it as: “a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way” (Convention on Biological Diversity (CBD), 2021). EBM addresses the interactions among ecosystem components, collective impacts of human activities, harmonizing sustainable use of nature, conservation, and equitable distribution of benefits gained from natural resources (Gelcich et al., 2018). It requires comprehension of various ecological and biological aspects, such as life cycles, trophic interactions, biodiversity, and carbon cycling, as well as abiotic measurements and thorough habitat mapping (Danovaro et al., 2017). The goal is to achieve a balance between conservation, sustainable use, and a fair and equal distribution of goods and ecosystem services that nature can offer. This means that in order to preserve the ecosystem's integrity and biodiversity, a thorough understanding of an ecosystem's function is necessary prior to any planned impact on the ecosystem (van der Meeren et al., 2021). EBM has received increased global attention over the past decade and has become a part of international conventions, dominating environmental policy debates. Global organizations, such as UN and The Food and Agriculture Organization (FAO), perceive it as the best strategy for deep-sea management (Gelcich et al., 2018; Guilhon et al., 2021).

3.3.2 Risk-reducing measures (Risk management strategies)

Deep-sea ecosystems targeted by the mining industry are in danger of loss of biodiversity, which is valued for the ecosystem services it provides. The organisms living in the deep-sea play essential roles in nutrient recycling and regulation of ocean acidification, as well as they provide provision of food, habitat, and nursery grounds for other species. It is thus essential to deal with potential risks and assure the conservation of a healthy and well-functioning deep-ocean biodiversity (Niner et al., 2018).

3.3.2.1 Mitigation hierarchy

A well-established method, called the mitigation hierarchy (Figure 7), addresses biodiversity-related risks and how the impacts on biodiversity can be reduced. It is a key tool in environmental management planning and is commonly required by regulatory frameworks. The main goal of this method is to ensure effective management of associated risks and impacts on the exposed areas (Niner et al., 2018; Tinto, 2008).

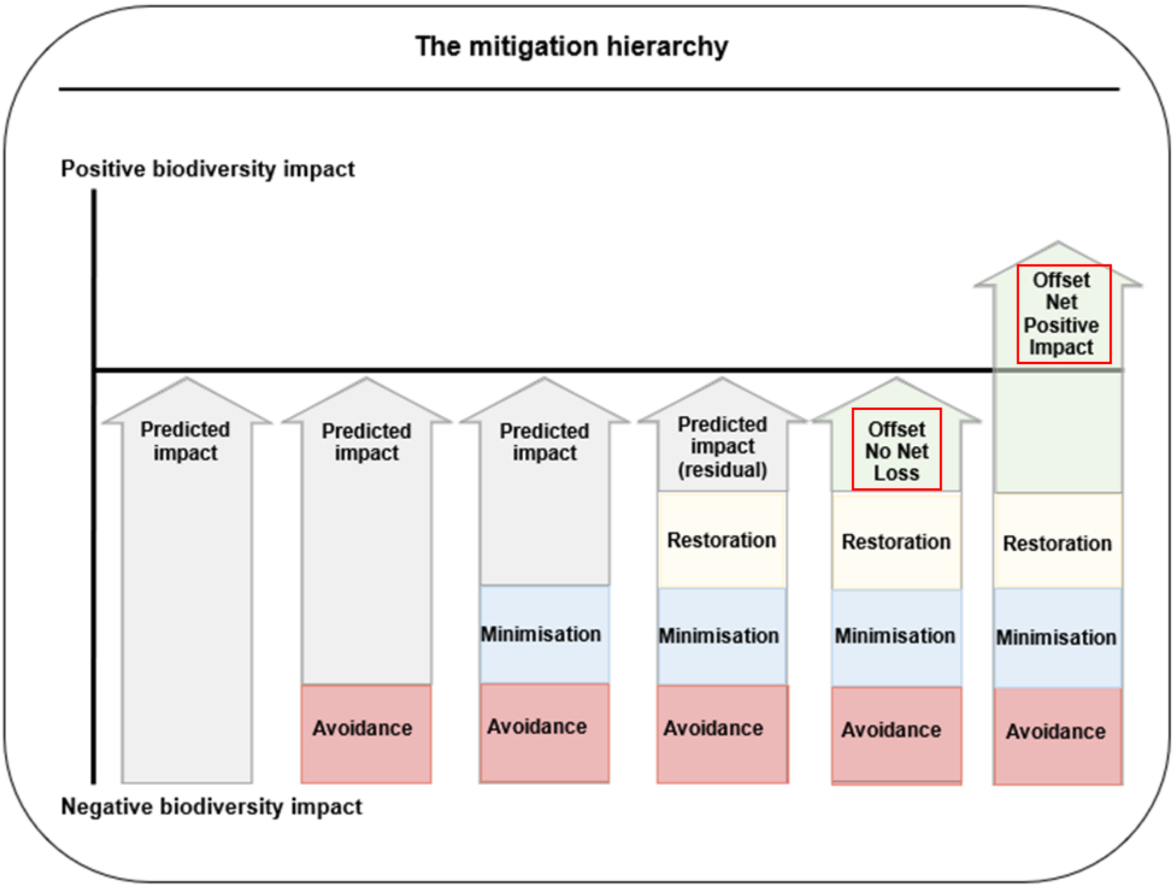

Figure 7. The mitigation hierarchy approach (Inspired by Tinto, 2008, p. 6).

As shown in Figure 7, the purpose of the mitigation hierarchy approach is to fundamentally seek avoidance, minimization, and restoration of the impacts to achieve a NPI on biodiversity. Avoidance refers to the decision to alter the expected course of action to prevent potentially adverse effects on biodiversity. It usually involves change or stop of activity, and it does not require continued effort to remove impacts. Minimizing the likelihood and severity of biodiversity losses and other ecosystem damage can be reduced but not completely prevented. This step comprises activities that require continuous action to lessen the significance of impacts and is applied when the activity cannot be avoided. After both avoidance and minimization have been considered and applied to the greatest extent, restoration aims to remediate and recreate habitats, biodiversity, and ecosystem services. To meet the NPI requirements, the restored biodiversity values should be at least equal to the original ones. At last, the residual adverse effects that cannot be avoided, minimized, or restored are managed by biodiversity offsets. These conservation actions are employed to manage residual impacts on biodiversity and aim to achieve “no net loss” or, ideally, a “net gain” of biodiversity (Business and Biodiversity Offsets Programme (BBOP), 2009; Niner et al., 2018; Tinto, 2008). However, several challenges related to the application of mitigation hierarchy to DSM arise due to the site complexity and knowledge gaps. These comprise quantification of biodiversity loss, perception of the significance of the loss, and justification of the loss in terms of benefits to the society (Niner et al., 2018).

3.3.2.2 Bow-tie technique

A Bow-tie diagram is one of the ISO 310100 risk assessment methods originating from the oil and gas industry for prevention, mitigation, and restoration controls of a risk management system. As seen in Figure 8, it is composed of a central knot, which represents the hazard event, left side chain that suggests prevention controls for the threats, and the right-side chain that represents the mitigation and recovery controls to reduce the consequences of such event (Cormier & Londsdale, 2020).

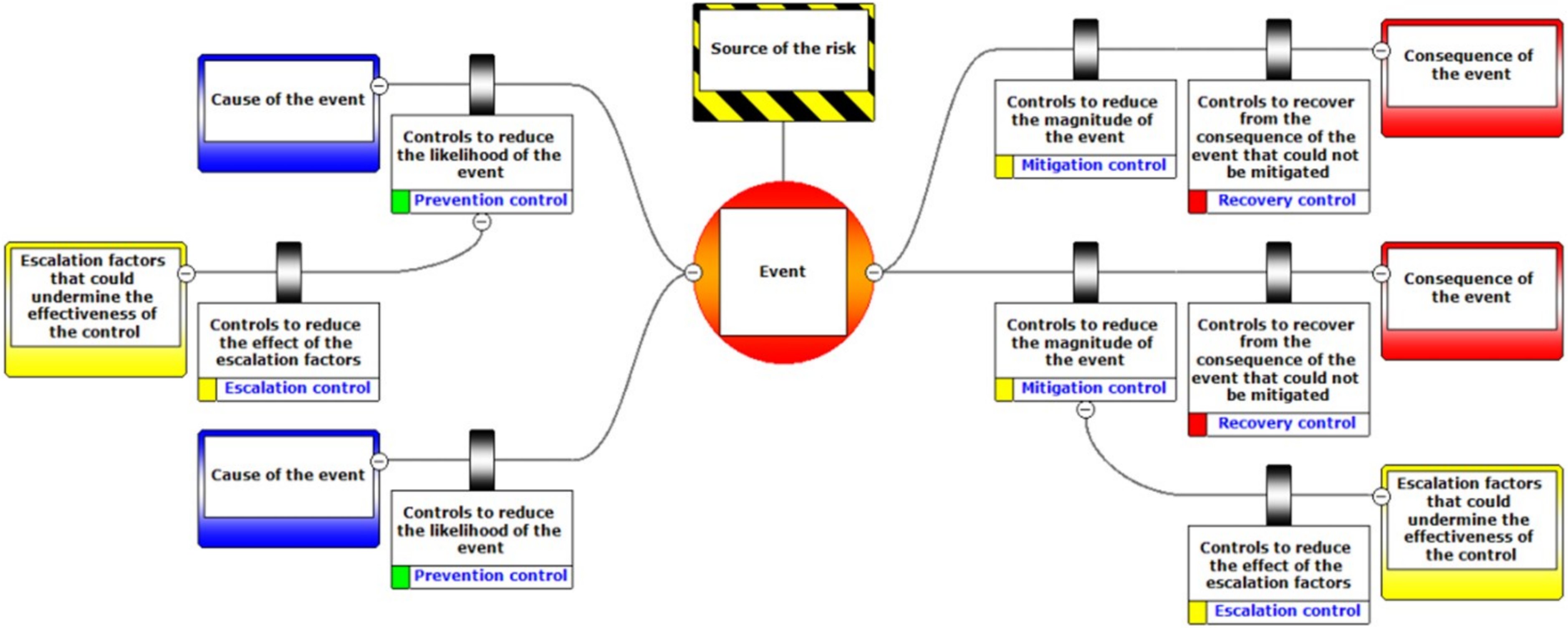

Figure 8. Structure of the bow-tie diagram (BowTieXP adaptation of IEC/ISO 31010). From «IEC/ISO Bowtie analysis of marine legislation: A case study of the marine strategy framework directive» by Cormier et al., 2018, International Council for the Exploration of the Sea (ICES), p.5. Copyright 2018, International Council for the Exploration of the Sea.

As a part of the risk assessment for the DSM, the bow-tie technique could be applied to analyse and demonstrate the role of environmental effects monitoring related to the introduction of energy and substances from the mining activities. When applying bow-tie to the DSM, the risk source can be the exploration and exploitation activities in the seabed (Figure 9). This source may lead to deleterious effects on the marine environment (the event) caused by the direct or indirect introduction of energy or substances. To reduce the likelihood of the event's occurrence, the introduction of energy and substances can be managed by prevention, reduction, and control measures (left side). Likewise, mitigation and recovery controls can be applied to reduce the harm to marine life as a consequence of the event and enhance the habitat recovery where the mitigation cannot be achieved (right side). Additionally, for large scale-operations, such as mining in the deep sea, the cumulative effects from other sources outside of the management control area can be difficult to segregate from the impact generated by the main activity. The bow-tie model allows cascading events to create a link to external consequences and provides a broader range of the causal pathways of risk (Cormier et al., 2018; Cormier & Londsdale, 2020).

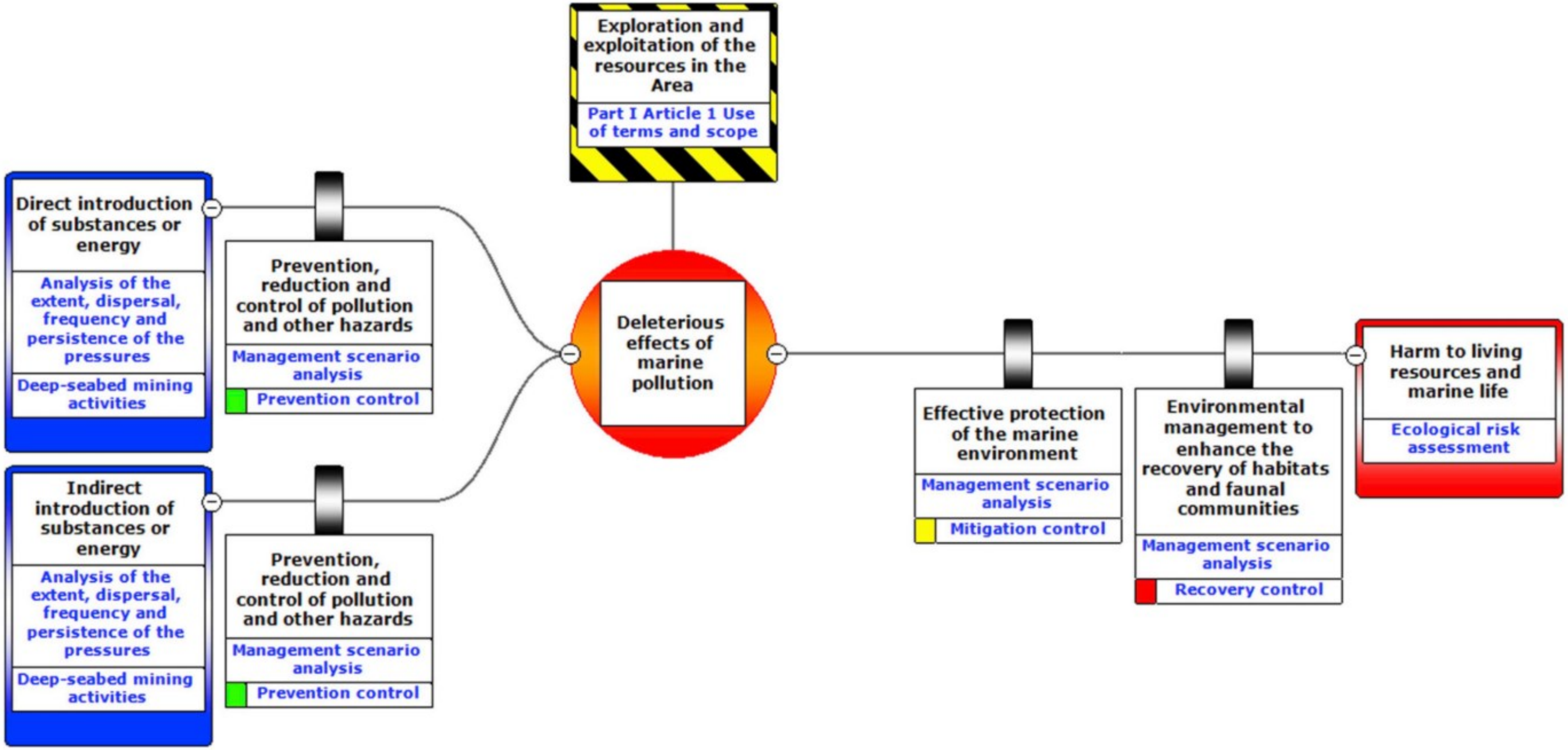

Figure 9. Bow-tie outline of the types of analysis and assessments. From «Risk assessment for DSM: An overview of risk» by Cormier and Londsdale, 2020, Marine Policy, p. 4. Copyright 2019, Elsevier Ltd.

3.3.3 Net positive impact

Continuously increasing human activity on land and in the oceans is essential for economic growth and development worldwide. At the same time, humans are responsible for nearly all reductions in natural ecosystem capacity, biodiversity loss, and species extinction. To minimize adverse effects on critical natural habitats and to contribute to biodiversity conservation, governments and the private sector must develop models for economically and environmentally sustainable development projects. The approach NPI approach addresses positive biodiversity goals and ensures that nature ultimately benefits from human activities (NPI Alliance, 2015; Tinto, 2008). NPI method is based on the mitigation hierarchy framework, where the goal for a given project is no net reduction in the biodiversity, long-term growth and reproduction, and functionality of communities and ecosystems. However, some biodiversity losses may be unavoidable and difficult to register due to knowledge gaps regarding the species and ecosystems of specific sites, and the restoration may differ regarding the space, time, or biodiversity type (Aiama et al., 2015). In addition, challenges related to NPI and application of the mitigation hierarchy method involve difficulties in quantifying biodiversity and predicting the overall ecosystem health, monitoring changes and identifying biodiversity gains, as well as combating long-term effects (NPI Alliance, 2015). Application of the mitigation hierarchy method to reach NPI goals for deep-sea ecosystems requires scientific research and data from the ERA to advance our knowledge in biological effects, biodiversity and trophic structure, connectivity and community dynamics, and ecosystem services (Van Dover, 2014).

3.3.4 Natural Capital

Natural capital (NC) can be determined as a reserve of natural resources utilized by humans to derive various life-supporting services (ecosystem services). These natural assets include land, water, air, minerals, fossil fuels, solar energy, and living things. Ecosystem services such as drinking water, crops, fuel, medicine, and building material are crucial to support the world’s economy and human life. Different compartments of NC also play essential roles in less visible ecosystem services such as climate regulation, carbon storage, natural flood defences, or pollination of crops (Convention on Biological Diversity (CBD), 2021). Similarly, the deep-sea communities provide a foundation for food, habitat, and nursery grounds for the species responsible for the recycling of nutrients and regulation of ocean climate change and acidification (Niner et al., 2018). Over-exhaustion of these services can be disastrous both in terms of biodiversity loss and ecosystem productivity. Therefore, proper management of NC is critical to sustaining ecological and socioeconomic safety and sustainability (Batker & Schmidt, 2015; Convention on Biological Diversity (CBD), 2021).

4 Results - Potential hazards of DSM with emphasis on SMS

Due to the lack of experimental data essential for conducting exposure and effect assessments, ERA is not yet possible to be properly performed. The focus of this thesis was to identify and evaluate potential hazards of SMS mining with associated consequences, exposure measures, effects on biota, and other environmental management factors, as a base for the development of an ecological risk assessment and management framework. A comprehensive list that also includes other forms of DSM is presented in Table 1.

Scientists have expressed concerns about the lack of knowledge in the biology, ecology, and diversity of species of the deep underwater habitats and how DSM might affect them. It is anticipated that DSM might destroy the deep-sea environments previously exposed to very little physical disturbance. These environments are dominated by diverse, rare and unique species, which are highly susceptible to long-term damage as they will likely take a very long time to recover from disturbance (Miller et al., 2018; Niner et al., 2018). The potential hazards of DSM on seabed species and habitats are likely to originate from physical disturbance, generation of sediment plumes, waste discharges, and other sources of pollution, including noise, light, and the release of toxic materials. The scale and range of potential hazards are still unknown, as the mining companies have not yet disclosed details of the proposed operating systems and waste management solutions (Chin & Hari, 2020).

The Norwegian Government has, in January 2021, decided to initiate an opening process for mineral activities on the Norwegian continental shelf in accordance with the Seabed Minerals Act. However, before an area can be opened for such activities, an impact (or consequence) assessment must be carried out as part of an opening process. An impact assessment program was proposed by the Norwegian Oil and Energy Directorate and commented by several researchers and industry actors (*Høring - forslag til konsekvensutredningsprogram for mineralvirksomhet på norsk kontinentalsokkel*, 2021). Table 1 presents a comprehensive list of potential hazards related to DSM with risk-related aspects and other environmental management-related aspects, which were drawn from points that were commented by different actors to the Oil Directorate in the Consequence programme hearing. The following sections contain a summarized description of the essential hazards of SMS mining with associated potential consequences for the marine environment.

Table 1. List of environmental risk-related factors (hazards, consequences, exposure characteristics, effects on biota, operational phase) and other environmental management-related factors (natural capital, mitigation, net positive impact) associated with DSM.

	Environmental risk factors						**Other environmental management factors**		
No.	**Hazard**	**Consequence**	**Exposure**		**Effects on biota**	**Operational phase**	**Natural capital**	**Mitigation**	**Net positive impact**
			Area affected	**Location of effects**					
1	Generation of sediment plumes (Christiansen et al., 2020)/ Dispersal of mineral particles at the seabed and surface water (van der Meeren et al., 2021)	- Released particles are subject to turbulent mixing and dispersal by the near-bottom currents (Christiansen et al., 2020). - Fine particles may resuspend at high current speeds and float around in the water column for months - Particles may spread and sediment at long distances from the initial source - Changes in the biochemistry and particle size in the sediment – the destruction of the ambient benthic fauna - Fine particles originating from surface units may contribute to the sealing of oral and respiratory systems and organs in zooplankton. Organisms that filtrate water may be exposed to particles tens of kilometres from the discharge area (van der Meeren et al., 2021) (see further No.12).	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Exploration and exploitation	- Communities in the deep sea provide the foundation for food, habitat, and nursery grounds for other species. Exhaustion may lead to weakened resilience of natural systems (van der Meeren et al., 2021). - The deep bathyal and the abyssal environments are characterized by very low sedimentation rates in the order of millimetres per 1000 years. Turbidity and particle load are usually very low - The deep-sea is generally a nutrient-poor environment and depends on the energy supply from the epipelagic zone (Christiansen et al., 2020).	- Identify environmentally safe scales of mineral mining operations - Estimate the extent of operational sediment plumes of mining operations with respect to particle concentrations in the water column that may affect the biota (Christiansen et al., 2020). - Use model and simulation tools to give realistic estimates for spreading, accumulation, and resuspension of fine particles both in the water column and at the seabed. This will provide the base for anticipation of industrial-scale impact and risk - Conduct effect studies to examine the tolerance in all relevant pelagic and benthic key species with respect to mineral particles and heavy metals (van der Meeren et al., 2021). - Quantify the physical and toxic effects of suspended particles and dissolved metals on organisms through laboratory and in situ experiments (Ribeiro, 2021).	- Dead animals associated with the mining activities may provide a short-term enhanced food supply for benthopelagic scavengers. It is not clear, however, whether this food source, which will comprise mainly small invertebrates, can be exploited to a large extent by the more mobile and rare scavengers which rely on odour plumes for the detection of food items (Christiansen et al., 2020).

	Environmental risk factors						**Other environmental management factors**		
No.	**Hazard**	**Consequence**	**Exposure**		**Effects on biota**	**Operational phase**	**Natural capital**	**Mitigation**	**Net positive impact**
			Area affected	**Location of effects**					
								Technology-dependence - Partly - The spreading of particles may be limited by proper technology.	
2	Contamination of water with microplastics (in relation to the ore transport) (van der Meeren et al., 2021)	- The transport of ore particles may cause wear and tear in pipes and lead to the formation of micro and nano plastics (van der Meeren et al., 2021).	Mostly near-site	Mostly water column	Mostly pelagic	Exploitation		- The number of plastics that potentially can be formed and released should be calculated. Other potential microplastic sources in the technology should also be considered (van der Meeren et al., 2021). Technology-dependence - Partly - Improvements in pipe materials and resistance to wear and tear.	
3	Contamination via return water (van der Meeren et al., 2021)	- Scarce methodology and technology for mining, washing, and concentration of ore minerals can result in the disposal of considerable amounts of waste containing heavy metals and process chemicals (van der Meeren et al., 2021). - Expected growth inhibition of phytoplankton and zooplankton caused by SMS leachate (Moodley, 2020).	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Exploitation	- The discharge of chemical particles in the surface waters may increase turbidity and lead to decreased light penetration. This may have a significant negative effect on the production of phytoplankton - The possible addition of inorganic nutrients may also contribute to increased primary production but not necessarily lead to a favourable composition and distribution of algae types and zooplankton. Increased turbidity may	- The pelagic ecosystem should be included in the baseline studies to evaluate the risk of mineral mining in the deep sea and discharge from surface units after the processing and dewatering (van der Meeren et al., 2021). Technology-dependence - Partly - Improvement on methodology - Improvement of pipe materials and resistance to wear and tear - Technology optimization by collecting process water - Pre-mitigation by ensuring that the return water is released close to the point of origin (the seafloor, resembling	

	Environmental risk factors						Other environmental management factors		
No.	Hazard	Consequence	Exposure		Effects on biota	Operational phase	Natural capital	Mitigation	Net positive impact
			Area affected	Location of effects					
							also affect the animals that use sight for predation or defence (fish, crayfish, amphipods, shrimps), while other predators that do not use sight, such as jellyfish, may gain competitive advantages (van der Meeren et al., 2021).	“backfilling”) (Moodley, 2020).	
4	Sludge production (van der Meeren et al., 2021)	- Microbial community disruption due to emission of heavy metals and other toxic substances and hypoxia. An oxygen-free environment can promote the growth of anaerobic bacteria and archaea and repress aerobic organisms. This may have negative effects on benthic organisms - Heavy metals may accumulate in bacteria and archaea intracellularly but may also precipitate, forming biofilms. Since bacteria and archaea are important food sources for zooplankton, there is an increased risk of accumulation of heavy metals further in the food chain leading to exposure to humans - Sludge particles may attach to fish eggs in the	Mostly near-site	Mostly seafloor	Mostly benthic	Exploitation	- Hydrothermal environments house complex microbial communities consisting of bacteria, archaea, single-celled eukaryotes and viruses, and other species that directly or indirectly are involved in biochemical sulfur, iron, and manganese cycles - Chemotrophic bacteria in the deep sea are important primary producers and nutrient sources for other organisms - Bacteria and archaea can be vulnerable when exposed to heavy metals, and huge amounts of sludge can have significant impacts on the composition and diversity of microbial	- Need for more studies that focus on non-active hydrothermal areas. There is uncertainty about how the microbial community structure is and what role it has in the food chain - Need for surveys of “anaerobic pockets” and their impact on the benthic habitats (van der Meeren et al., 2021). Sediment/water experiments in the lab and field may clarify the extent of these effects. Technology-dependence - Possibly - Development of technology that minimizes deposition and exposure to sludge.	

No.	Environmental risk factors						Other environmental management factors		
	Hazard	**Consequence**	**Exposure**		**Effects on biota**	**Operational phase**	**Natural capital**	**Mitigation**	**Net positive impact**
			Area affected	**Location of effects**					
		sediment and reduce the buoyance (which is important for the survival and spreading of eggs), which in turn may increase the predation of eggs along the bottom (van der Meeren et al., 2021).					communities (van der Meeren et al., 2021).		
5	Light and noise pollution (van der Meeren et al., 2021)	- Artificial light sources at the surface or in the deepwater may affect the daily vertical migration of organisms and disturb the feeding, reproduction, and pray-predator relationships - Attraction to light may enhance the danger of hydraulic entrainment. - The ecological function of bioluminescence may be masked by artificial light. - The organisms that are attracted by the light may risk vision damage and increased mortality. Artificial light also affects eating behaviour, distribution, risk of predation, migration, and reproduction. Light may attract bigger predator fishes that use vision to hunt and result in the increased top-down regulation of fish populations	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Prospecting/ Pre-studies, exploration and exploitation	- Many deep-sea organisms have partly or completely reduced eyes or light-sensing organs. Some fishes are known to be attracted to light, whereas others avoid it or don't show any reactions - Bioluminescence is produced by a wide variety of organisms (from bacteria to fish) and is the only natural light source in the deep sea. It is used for communication, for example, mate finding - Deep-sea fishes may use sound for communication, and mechanoreception is probably important in deep-sea scavengers for the near-field detection of food falls (van der Meeren et al., 2021) Marine mammals (whales) use the	- Lack of knowledge about light and noise pollution makes it difficult to evaluate potential effects (van der Meeren et al., 2021). - The role of sound in deep-sea ecosystems is largely unknown in contrast to the upper water column (Christiansen et al. 2020) Technology-dependence - Little - Light exposure is area-limited - Noise exposure can be more widespread (and serious). - Development of technology that reduces light and noise pollution	

	Environmental risk factors						Other environmental management factors		
No.	Hazard	Consequence	Exposure		Effects on biota	Operational phase	Natural capital	Mitigation	Net positive impact
			Area affected	Location of effects					
		- Noise from the mining gear may travel distances of hundreds of kilometres and impact large areas. It may disrupt the deep-sea communities by masking the biological relevant noises or by triggering false answers. It is also likely to reach the upper water column and affect mammals and other marine life in surface waters (van der Meeren et al., 2021). It may also have noise effects in the SOFAR channel, thus spreading the noise to particularly faraway locations.					SOFAR channel for communication.		
6	Seismic surveys (Miljødirektoratet, 2021)		Near-site Far-site	Seafloor Water column	Benthic Pelagic	Prospecting/ Pre-studies, exploration, and exploitation			
7	Impact of mining gear on the deep seabed geology (Miljødirektoratet, 2021)	- The movement of mining gear and inflicted shaking of the seabed may alter the seabed structure and/or reactivate inactive hydrothermal sources or alter the paths of the hot outflow, which may cause recolonization or extermination of specific fauna (Miljødirektoratet, 2021).	Near-site	Seafloor	Benthic	Exploration and exploitation	- Geochemical variables are key drivers of community composition and structure - The seabed environment and fauna depend on the type of geology (active hydrothermal sources, inactive hydrothermal sources, or deceased hydrothermal sources)	- Need to examine how the movement and shaking of the seabed will impact the seabed geology and how vulnerable the environment is to geochemical changes - Optimize technology to minimize the damage (Miljødirektoratet, 2021). Technology-dependence - Partly	

	Environmental risk factors						Other environmental management factors		
No.	**Hazard**	**Consequence**	**Exposure**		**Effects on biota**	**Operational phase**	**Natural capital**	**Mitigation**	**Net positive impact**
			Area affected	**Location of effects**					
							(Miljødirektoratet, 2021).	- Optimization of the mining gear.	
8	Generation of sulfuric acid (van der Meeren et al., 2021)	- The mining of sulfide deposits has the potential to generate sulphuric acid in the sea bottom - The ocean acidification effect may be elevated locally due to the release of sulfuric acid (van der Meeren et al., 2021)	Near-site	Seafloor	Benthic	Exploration Exploitation		Scale-dependent - The extent to which sulfuric acid may contribute to ocean acidification is uncertain (the seawater is well buffered) Improvement of knowledge of sulphuric acid generation in the sea bottom.	
9	Ocean acidification (van der Meeren et al., 2021)	- CO_2 emissions to the atmosphere associated with mining activity are expected to rise. This may, in turn, have negative effects on marine life due to ocean acidification (van der Meeren et al., 2021)	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Prospecting/ Pre-studies Exploration Exploitation	- Low pH in the water results in the decrease of hydroxyl and carbonate ions which affects the distribution, release, and availability of metals that form strong complexes with these ions - Some of the metals, such as iron, manganese, and zinc, are necessary for growth, and the reduced availability of these may negatively affect biological reproduction - Reduction in the pH may also affect the binding or adsorption to organic matter and may alter the liberation and toxicity of different heavy metals such as	- It is known that organic copper and cadmium may decrease by 10% due to ocean acidification, while organic cobalt and nickel may increase. However, more information about the potential effects on marine ecosystems due to these changes is required. The effect assessment should therefore consider mineral mining also from the climate perspective (van der Meeren et al., 2021). Technology-dependence - Partly - Technology optimization to reduce CO_2 emissions.	- The minerals extracted from the deep sea will mainly be used to produce batteries and contribute to the electrification and the green shift. Thereby, the global CO_2 emissions to the atmosphere originating from the means of coal or oil and gas-driven industries and transport may be overall reduced (van der Meeren et al., 2021).

	Environmental risk factors						Other environmental management factors		
No.	**Hazard**	**Consequence**	**Exposure**		**Effects on biota**	**Operational phase**	**Natural capital**	**Mitigation**	**Net positive impact**
			Area affected	**Location of effects**					
							mercury, lead, cadmium, nickel and cobalt (van der Meeren et al., 2021).		
10	Altered carbon storage in the deep seabed (Miljødirektoratet, 2021)	- Disturbance of the sediment may inflict the release of organic carbon (Miljødirektoratet, 2021).	Near-site	Seafloor	Benthic	Exploitation	- Marine deep-sea sediment is one of the world's biggest organic carbon storage (Miljødirektoratet, 2021).	- Need to investigate how the mining activity will affect the carbon storage and associated processes (Miljødirektoratet, 2021). - Studies of seafloor functioning and carbon turnover may clarify the effects and magnitude.	
11	Alteration of abiotic parameters at mining sites (Ribeiro, 2021)	- Mining may inflict physicochemical changes in the water column caused by suspended particles or dissolved metals (Ribeiro, 2021).	Near-site (Far-site)	Seafloor Water column	Benthic Pelagic	Exploitation	- Communities in the deep sea are affected by a number of environmental variables such as water temperature, nutrients, and geochemistry (Ribeiro, 2021).	- *In situ* monitoring of abiotic parameters over time in potential mining sites is important to identify important environmental factors and their natural variability, as well as to discover changes in the environment inflicted by the mining (Ribeiro, 2021).	
12	Accumulation of particles, heavy metals, and chemicals in the food chain (van der Meeren et al., 2021)	- Bioaccumulation of toxic components may result in acute or chronic effects in organisms - Heavy metals accumulate over time and may affect the growth, development, reproduction, and survival of fish by affecting the physiological, biochemical, metabolic, systematic, and genetic functions (van der Meeren et al., 2021).	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Exploration Exploitation	- Acute and chronic effects may result in altered development, growth inhibition, lower reproduction rates, and elevated death rates - Higher trophic levels may be particularly vulnerable due to bioaccumulation in the food chain - The area exposed to particles can easily expand through partial	- With regards to food safety, there is a need to investigate to what extent mineral mining in the Norwegian sea may elevate levels of heavy metals in organisms that already might have high values from natural sources. Exceedances of boundary values may affect the export of fish and lead to the closure of fisheries (van der Meeren et al., 2021). Technology-dependence - Partly (related to No.1)	

No.	Environmental risk factors						Other environmental management factors		
	Hazard	Consequence	Exposure		Effects on biota	Operational phase	Natural capital	Mitigation	Net positive impact
			Area affected	Location of effects					
							exposure of plankton that migrates both vertically and horizontally (van der Meeren et al., 2021).	- Development of technology that minimizes exposures.	
13	Removal of the substrate (van der Meeren et al., 2021)	- Loss of habitat is associated with the removal of the sediment (van der Meeren et al., 2021). - Non-avoidable near-field effects.	Near-site	Seafloor	Benthic	Exploration and exploitation	- Bottom-dwelling organisms will most likely not survive the mining process. This may also have an impact on fish spawning in the area - Permanent removal of the substrate may disturb the connection between bottom-dwelling and benthopelagic communities (van der Meeren et al., 2021).	- Collect data to establish security margin (van der Meeren et al., 2021). <u>Technology-dependence</u> - Little - Restore/recolonize the area after the operation.	
14	Removal of habitat-forming, slow-growing benthic fauna (Christiansen et al., 2020)	- Impairment of processes associated with feeding, growth, and reproduction - The removal of habitat-forming, slow-growing benthic fauna such as corals and sponges will have a long-lasting negative effect on pelagic animals utilizing this habitat for food or shelter - The altered composition of benthic fauna will affect trophic pathways between benthic and benthopelagic organisms and thus may	Near-site	Seafloor	Benthic	Exploration and exploitation	Deep-sea pelagic and benthopelagic communities at bathyal and abyssal depths can be considered to form the largest reservoir of animal diversity on earth. The benthopelagic community is the least known compartment of the deep-sea realm.	Collect knowledge of deep-water communities and ecosystems functioning. Need for quantitative assessments of mining impacts and an overall evaluation of the extent of the harm that may be caused. <u>Technology-dependence</u> - Partly (related to No.1).	

	Environmental risk factors						**Other environmental management factors**		
No.	**Hazard**	**Consequence**	**Exposure**		**Effects on biota**	**Operational phase**	**Natural capital**	**Mitigation**	**Net positive impact**
			Area affected	**Location of effects**					
		favour or discriminate against certain feeding interactions and ultimately change the composition of the benthopelagic communities (Christiansen et al., 2020).							
15	Removal of ambient water (Christiansen et al., 2020)	- Meroplanktonic larvae and eggs may be sucked up together with the water by suction devices and killed. Since fishes in the deep sea appear more sluggish than the pelagic fishes (less turbulence), they may have a lower ability to avoid disturbances and also be sucked up - The water used for pumping the ore will be warmed up in the upper water layers. The release of water different from ambient temperature may cause direct biological effects as bathyal and abyssal fauna are adapted to low temperatures with very little variation (see also No.5 for possible combination with light and hydraulic entrainment) (Christiansen et al., 2020).	Near-site	Seafloor Water column	Benthic Pelagic	Exploration and exploitation	- The area directly above the seafloor is the habitat of a specific benthopelagic fauna, including fishes, larger invertebrates, and zooplankton, which are substantially different from the overlying water column. In this layer, there is also retention of meroplankton larvae of benthic invertebrates (Christiansen et al., 2020).	Technology-dependence - Partly - Optimization of suction devices - Possibly use of filters to prevent suction of the fauna.	
16	Introduction of alien species or pathogenic material	The transport of solid material and water from the seafloor to the surface, as well as the transport of the tailings into the deep sea,	Near-site	Seafloor Water column	Benthic Pelagic	Exploration and exploitation		- No studies were found addressing this issue.	

No.	Environmental risk factors						Other environmental management factors		
	Hazard	Consequence	Exposure		Effects on biota	Operational phase	Natural capital	Mitigation	Net positive impact
			Area affected	Location of effects					
	(Christiansen et al., 2020)	will also include animals, microbes, and viruses which may remain viable and pose a potential health risk to the established communities (Christiansen et al., 2020).							
17	Loss of unknown deep-sea fauna (NORCE, 2021)	- There is little knowledge of species diversity in the deep sea. The significance of the risks of mining activity to the fauna is, therefore, uncertain (NORCE, 2021).	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Exploration and exploitation	95% of species in the deep sea are presumably still undescribed (NORCE, 2021).	It is suggested that at least 70 % of the species in the mining area should be described. The study should include genome-based techniques and include the variation in species diversity over time (seasons) (NORCE, 2021). Technology-dependence - Partly - Development of improved methods (DNA-based taxonomy).	Some of the unknown species in the deep sea might benefit from the impacts of the mining activity.
18	Effects on marine mammals (van der Meeren et al., 2021)	The effect will depend on the scope in time and space and the technology used (van der Meeren et al., 2021).	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Exploration and exploitation	- Several marine mammals can be found in the anticipated mining area: baleen whales, toothed whales, beaked whales, killer whales, sperm whales, humpback whales, and seals (van der Meeren et al., 2021).	- Collect knowledge about the distribution and activity of marine mammals in the mining area and the potential effects that mining activity may cause (van der Meeren et al., 2021). Technology-dependence - Uncertain - Noise may be the biggest concern due to the potential for disturbance of whale communication (see further, e.g. No.5).	

	Environmental risk factors						Other environmental management factors		
No.	Hazard	Consequence	Exposure		Effects on biota	Operational phase	Natural capital	Mitigation	Net positive impact
			Area affected	Location of effects					
19	Effects on other industries (Ribeiro, 2021)	- Reduced access to areas for scientific studies - Reduced capacity for the development of bioprospecting - Loss of species that can otherwise provide valuable marine genetic resources (Ribeiro, 2021).	Near-site Far-site	Seafloor Water column	Benthic Pelagic	Exploration and exploitation	- Biological communities with a high potential for valuable marine genetic resources (Ribeiro, 2021).	- Coexistence with scientific research during exploration activities should be clarified and regulated, and regulations should ensure that independent research institutions have access to areas under investigation and mining (Ribeiro, 2021).	
20	On-land deposition of the tailings (Miljødirektoratet, 2021)	- Inflict area-wise problems on land - Introduction of toxic particles to land-based ecosystems through acid mine drainage. This can result in leaching and erosion with subsequent formation of sinkholes, contamination of soil and groundwater, and loss of biodiversity (Miljødirektoratet, 2021).	Terrestrial	Limnic Soil	Terrestrial ecosystem	Exploitation		- Frequent monitoring and treatment of water passing through are required - Consider an alternative for deposition in the sea (Miljødirektoratet, 2021). Technology-dependence - Partly - Avoid risks by alternative deposition in the sea.	
21	Impacts associated with the closure of the activity (NIVA, 2021)	- The impacts of seabed mining on the fauna, habitat, ecosystem functioning, and services (pelagic and benthic) are expected to be significantly larger than those of an O&G activity (NIVA, 2021).	Near-site	Seafloor Water column	Benthic Pelagic	Closure		- Specific closure provisions should be considered for seabed mining, in addition to any provisions that can be adapted from the O&G regulations (NIVA, 2021).	

4.1 Sediment plumes

Sediment plumes are clouds formed by sediment particles when spread in water by prevailing currents. They present the most serious potential source of environmental impacts from DSM and are expected to potentially be formed on the seafloor, as well as in the water column by the machinery movement, leakages from riser pipes, accidental spillages and wastewater disposal (Gjerde et al., 2016; Miller et al., 2018). Sediment plumes may travel short or long distances, all depending on the sediment grain size, its shape, density and concentration, the sinking velocity, coagulation potential, and other factors such as water temperature, density, and current speeds. The potential impacts of sediment plumes will vary depending on the design and operation of the machinery, biochemical and toxicological properties of plume particles, deposition rates, and species occurrence in the deposition zone. The sediments of deep ocean abyssal plains are composed of very fine particle sizes. Hence, due to the extremely slow sinking velocity of such particles, the impacts of DSM could affect benthic and pelagic ecosystems far beyond the actual mining site. There are knowledge gaps associated with the characteristics of the plumes – vertical and horizontal movement, metal composition, toxicity, and the effects of sedimentation on little-studied deep-sea habitats. However, the research on near-surface plumes shows a potential to cause plankton blooms due to a rapid release of nutrients into nutrient-poor waters. The upper water layers of the open ocean have typically very low concentrations of nutrients and trace metals such as iron, zinc and cadmium, limiting phytoplankton growth. Sediment plume release at the surface could cause phytoplankton blooms and lead to bioaccumulation of toxic metals in the food webs. This may affect the horizontal migration of species, such as birds, sharks, and marine mammals, that feed on plankton. Vertical migrations from deep waters to the surface by small pelagic fishes, shrimps, and squids may also be disturbed by near-surface plumes (Chin & Hari, 2020).

Generally, DSM would occur in habitats that are typically very stable and where species are not adapted to high levels of sedimentation. Natural sedimentation rates in such habitats are very low, down to 1-2 millimetres per thousand years. Therefore, sediment plumes could potentially alter sediment characteristics which could affect deposit-feeding fauna, smother organisms, clog up filter feeders, and bury seabed fauna (Amon et al., 2022; Gjerde et al., 2016). The details of mining machinery are still unknown but computer models predict that some of the disturbed sediment might change the structure and form sporadic lumps on the seabed, which may lead to changes in community composition (Becker et al., 2001; Gjerde et al., 2016). Increased turbidity may also affect species that depend on bioluminescence for catching prey, communication, and defence against predators (Chin & Hari, 2020). Particularly for SMS mining, the plumes may also carry toxic chemicals which can get released when ore deposits are exposed to oxygen during the mining process (Gjerde et al., 2016).

4.2 Contaminant release and toxicity

The release of potentially toxic substances into the marine environment during DSM is associated with the mining process itself, as well as with the discharge of sediment plumes and returned seawater plumes (Christiansen et al., 2020; World Bank, 2017). The processing of mineral ore occurs in different steps and requires different chemicals (Ramirez-Llodra et al., 2015). These process chemicals and potentially toxic ore elements that may leak from sulphide-rich ores will eventually reach the ocean by the seawater plume recovered from the mineralized material. However, the bioavailability and toxicity of released chemicals will highly depend on environmental conditions, such as the pH, alkalinity, and organic material (Christiansen et al., 2020; World Bank, 2017). The seawater plume is expected to have a different temperature, salinity, dissolved and suspended mineral concentration etc., than the ambient water it would be released into. If released into surface water, it may have a great impact on the fauna living in the photic zone. Depending on the nutrient content and other earlier mentioned factors, the seawater plume may reduce phytoplankton growth, contribute to increased primary production, increase water turbidity and lead to decreased light penetration which would affect fauna that uses sight for predation or defence, decrease dissolved oxygen concentration, and increase heavy metal loads. However, the volume of returned water may vary depending on the technology used and is expected to carry smaller amounts of suspended sediments than the operational plume (World Bank, 2017).

4.3 Noise and light pollution

Noise and light pollution is the increase in noise and light levels above natural ambient levels as a result of human activities (Chin & Hari, 2020). Apart from DSM, there are already several noise pollution sources in the marine environments, among others, sounds from ships and boats, submarines and seismic surveys. The potential effects of noise pollution from mining activity will vary with sound level, duration, spectrum, temporal pattern, and distance from the source. Depending on the strength of the sound and distance from the source, it may cause behavioural and physiological alterations in individual animals, affect population connectivity, and lead to ecosystem shifts (Figure 10). The intense sound may even cause physical damage to the auditory system and rupture organs or blood vessels. Latest research has shown that noise pollution may alter the swimming behaviour of fishes, affect their spawning and feeding activities, reduce their survival, as well as it may have significant effects on the species that rely on sound for communication by masking the biologically relevant noises (Jones, 2019; Slabbekoorn, 2019).

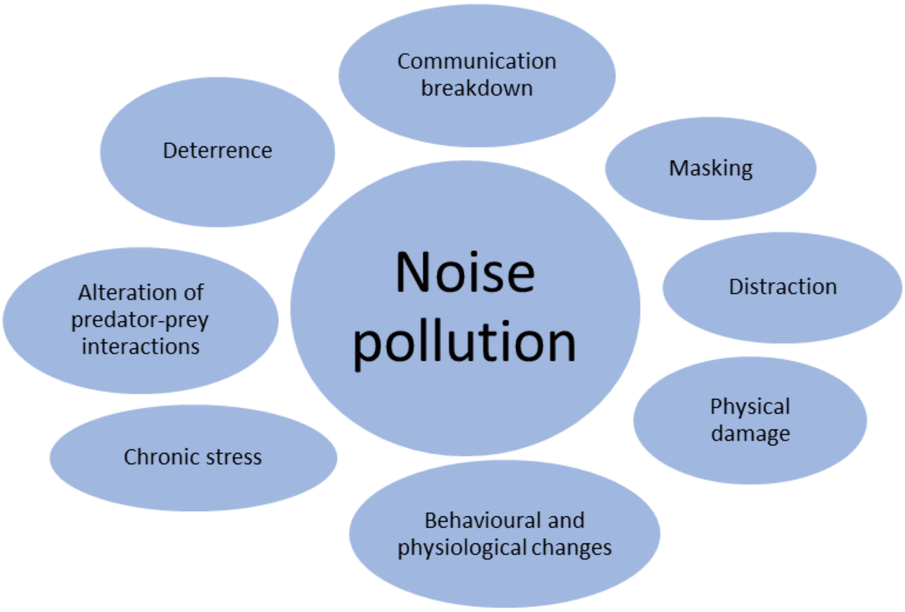

Figure 10. Potential effects of noise pollution for deep-sea species (Inspired by Slabbekoorn, 2019, p.2).

Marine mammals tend to have long-range foraging trips and migrate long distances. This makes them particularly sensitive to elevated noise levels that may cause deviation in migratory pathways (Slabbekoorn, 2019). Furthermore, marine mammals (in particular whales) use a Sound Fixing and Ranging channel (the SOFAR channel) for communication with other whales located many kilometres away. The SOFAR channel is a horizontal layer of water at the bottom of the thermocline where the sound bounces between distinct water layers and can travel for thousands of kilometres without losing significant energy (Figure 11). Sounds such as earthquakes, whale calls, and artificial noises can be detected by hydrophones occurring from vast distances (NOAA, 2021; Payne & Webb, 1971).

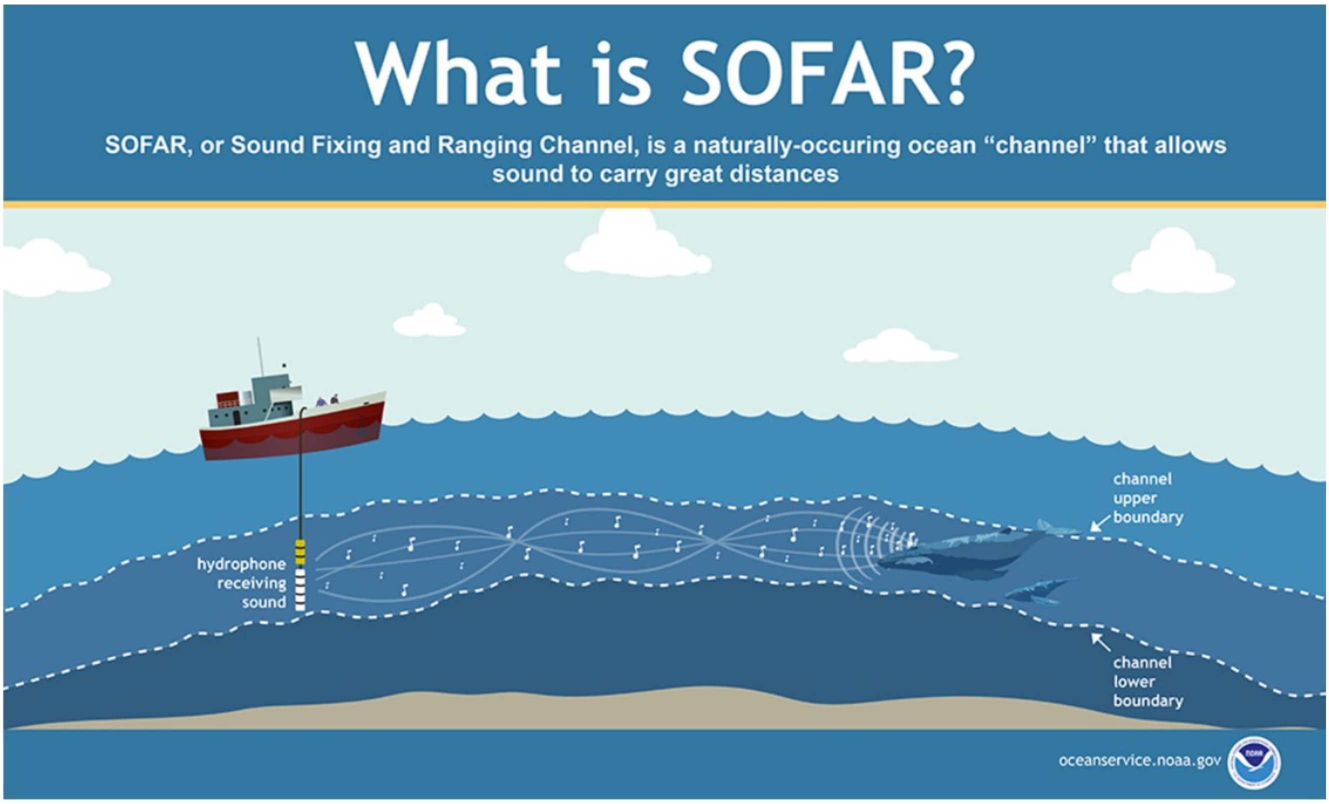

Figure 11. «This infographic illustrates how SOFAR works. It shows a ship with a deployed underwater hydrophone receiving the sounds of distant whales, thanks to the effects of the SOFAR channel», 2021, by NOAA. (https://oceanservice.noaa.gov/facts/sofar.html).

In addition to noise, light pollution is also a concern in marine environments. Research on artificial light originating from offshore infrastructure, coastal development, shipping, and fishing shows various impacts on marine ecosystems, including disorientation and mortality of sea turtle hatchlings and birds, the aggregation and exploitation of fish and squid, altered composition of sessile invertebrate communities, and more (Davies et al., 2016). The DSM would be another artificial light source both at the surface, seabed and possibly mid-water depths, affecting a wide range of species. The species living in deep abyssal waters have adapted to completely dark conditions and have partly or completely reduced eyes or light-sensing organs (Chin & Hari, 2020; Christiansen et al., 2020). Such species may thus be very vulnerable to lights from artificial sources, and permanently damaged vision might be suspected. Lights originating from DSM infrastructure may also impact the vertical migration of pelagic and mid-water species and alter the foraging behaviour of certain fishes. In particular, lighting could interfere with biotic interactions mediated by bioluminescence (Chin & Hari, 2020).

4.4 Mine waste

Large volumes of waste are produced by the mining activity through crushing and milling of the ore to separate minerals. The fine-fraction slurry waste may include diverse chemicals used for the processing of the ore. Particularly, mining SMS deposits will generate fine-grained cuttings by drilling/excavation and create plumes of fine sediment and SMS tailings. Near-field and surrounding background sediments will potentially be exposed to solids and leachates of SMS tailings. Due to the potential toxicity of SMS tailings, mine waste management is considered one of the most significant environmental issues (Moodley, 2020; Ramirez-Llodra et al., 2015).

There are three main types of tailings disposal in the sea: coastal shallow-water disposal (CTD), submarine tailings disposal (STD) and deep-sea tailing placement (DSTP) (Figure 12). CTD disposal appears in the euphotic zone in shallow coastal waters and has direct impacts on euphotic marine systems and shorelines. In STD, the tailings are disposed to submerged water depths, still in the euphotic zone, but the discharge creates a deposit flow to deeper areas resulting in gravity sedimentation below the euphotic zone. Finally, the DSTP is the disposal of tailings in depths >100 metres resulting in the deposition of tailings on the deep seafloor below 1000 metres. The depth at which mine waste will be deposited is a critical ecological and environmental factor for the ambient ecosystems (Ramirez-Llodra et al., 2015).

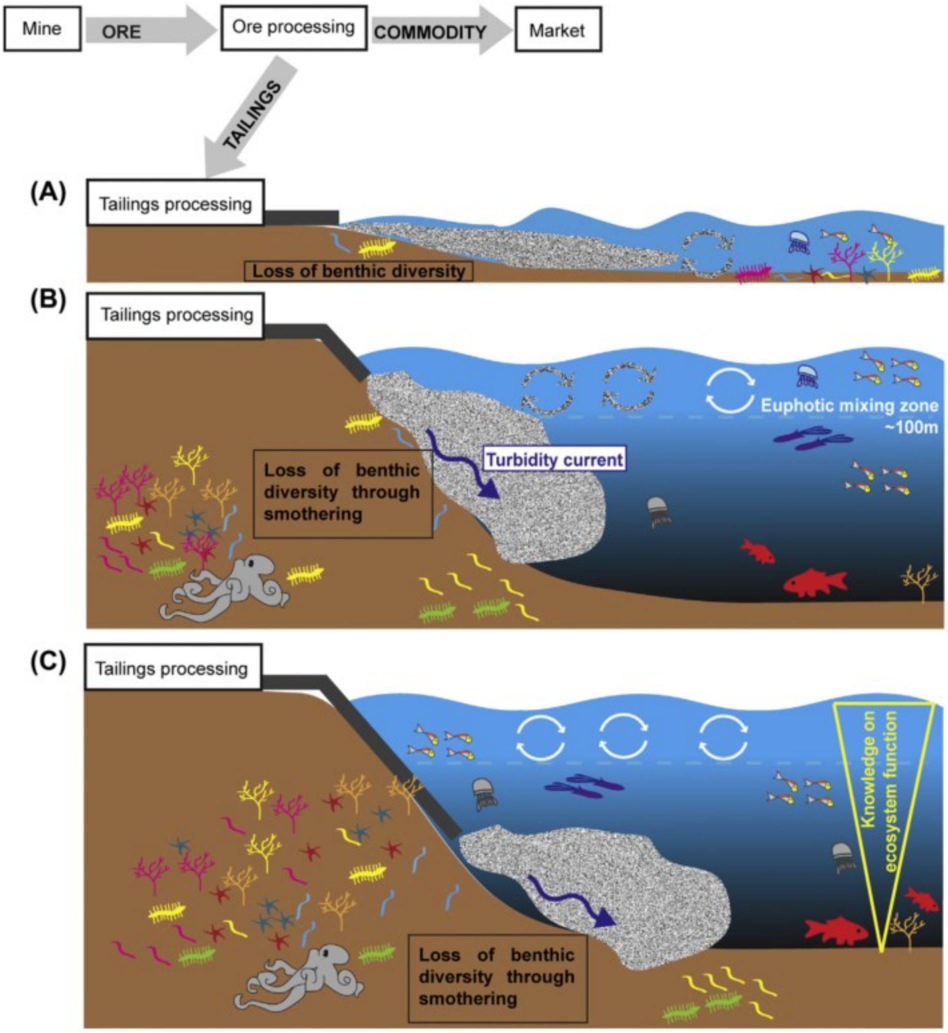

Figure 12. Schematic representation of the three main methods for mine tailings disposal: (A) CTD, (B) STD, and (C) DSTP. From «Submarine and deep-sea mine tailing placements: A review of current practices, environmental issues, natural analogues and knowledge gaps in Norway and internationally» by Ramirez-Llodra et al., 2015, Marine Pollution Bulletin, p. 17. Copyright 2015, Elsevier Ltd.

5 Discussion

Until now, mining activities around the world have taken place on land. There is, therefore, limited knowledge regarding the extent of the environmental risk of mining in the deep sea. Oslo and Paris Commission (OSPAR) guidelines for assessing environmental risks and reducing pollution from offshore oil and gas activities are the most comprehensive in the context of ERA for the marine environment and have been applied in the industry for many years. These guidelines are also relevant for the input to an ERA of SMS mineral mining and can be used for assessing risk to the environment. However, due to the knowledge gaps in deep-sea ecology, there is a need for an improved methodology to understand better the impacts of the mining activity on the deep-sea environment. A major uncertainty associated with the use of OSPAR guidelines on ecotoxicology testing for deep-sea SMS mining is the ecological relevance of surrogate organisms. The biodiversity in the deep sea is considered extremely high, and a great majority of species are still undescribed, which imposes limitations for community studies. The lack of information on species distribution and other scientific knowledge gaps should be addressed as a precursor to effective deep-sea risk evaluation and management (Ahnert & Borowski, 2000).

Some researchers and industrial actors state that the excavation of minerals from the deep sea is essential for the global transition to renewable energy (Batker & Schmidt, 2015; Chin & Hari, 2020). However, others point out that it is not clear how much new metal is needed, considering already existing mineral stocks and recycling of these, the development of circular economies, and alternative sources of metals (NORCE, 2021). Some industrial actors even suggest that we may not need increasing amounts of minerals to support the green shift as the battery technology is evolving rapidly and the research focus on new solutions that are less dependent on nickel and cobalt (Leisegang et al., 2019). A comprehensive analysis should therefore be carried out to clarify all the uncertainties regarding current and future mineral needs.

5.1 Risk framework

DSM is a new emerging industry in a part of the planet that is nearly unexplored (Amon et al., 2022). There are three distinct sources of minerals that occur in distinct seafloor settings and host different ecosystems: manganese nodules, cobalt crusts, and seafloor massive sulphides (Weaver & Billett, 2019). Although the identified hazards of mineral mining are mutual for all three sources, it seems that the importance, relevance, and priority of some hazards will vary due to the differences in mining methods, sediment characteristics, depth, and ecosystem structure. As nodule mining will need to take place in large seabed areas (Weaver & Billett, 2019), it is reasonable to suggest that the environmental and ecological impacts would be larger and more significant than mining SMS, which would occur in smaller restricted areas. Scale seems to be one of the most important factors for evaluating and comparing the severity of impacts of mining of mineral resources. Amon et al. (2022) suggest that common impacts from the mining of all three mineral sources will be associated with the removal of the resource, generation of sediment plumes, chemical contamination and increase in noise, vibration, and light. However, even though all three mineral sources act as a substrate/habitat for sessile fauna, the potential direct impact on biodiversity due to the removal of SMS deposits will be significantly lesser (< 10 square kilometres per mine) compared to the removal of nodules (6-15,000 square kilometres per mine), and crusts (10-100 square kilometres per mine). In addition, the most distinct organisms are often found at active hydrothermal vents, and species occurrence moving away from the active vents are more similar to those from the surrounding continental slopes. Given that the SMS ores would be mined some distance away from the active vents, as these are too hot to be mined, the impact on hydrothermal vent ecosystems from more far away mining sites may therefore be considered relatively small (Weaver & Billett, 2019). The generation of sediment plumes is also expected to be much smaller for SMS (up to 38,000 cubic metre per day) compared to the mining of nodules (up to 80,000 cubic metre per day) based on the projected resource extraction rates and the area of impact. However, the spatial scale of impact is still unclear due to insufficient knowledge about the properties of the sediment plumes and the tolerance of ambient fauna (Amon et al., 2022). Additionally, of all three DSM sources, SMS deposits will be most similar to deposits mined on land, and they can be found in relatively shallow water depths compared to nodule mining which takes place at abyssal depths. This suggests that the existing mining technology used on land could be adapted to SMS mining rather than being invented as for nodules and crusts (Weaver & Billett, 2019).

It is reasonable to think that to obtain relevant data for the risk evaluation of the deep-sea environment, it is crucial to expand our knowledge of the potential hazards of DSM. Based on the literature and information presented in Table 1, sediment plume generation, chemical contamination, noise and light pollution, and mine waste management seem to be the most important hazards for mining of SMS (these will be discussed in separate paragraphs below). There are, however, large scientific knowledge gaps in environmental baselines, impacts, resilience, and management associated with SMS mining, which are important to address as a precursor to effective deep-sea management (Amon et al., 2022).

5.1.1 Bow-tie analysis

Cormier and Londsdale (2020) suggest that the challenges and knowledge gaps associated with DSM lie not only in science but also in the management and engineering processes. Concerns such as sediment plume management during mining operation and processing should be addressed and analysed as a part of the assessment. In addition to current ERA approaches, risk analysis should include a detailed overview of the potential prevention, mitigation, and recovery controls as a part of environmental management to protect the marine environment. One may suggest that the relevance of the application of the Bow-tie technique to SMS mining emerges from the need to integrate the causal pathways of risk that can result in harmful effects on the consequences to the marine environment with the effectiveness analysis of the prevention and mitigation controls. A complete Bow-tie of SMS mining would comprise the specific events (hazards), their causes and consequences, and thorough prevention, mitigation, and recovery options (Cormier & Londsdale, 2020). Such work would provide grounds for the analysis of causal pathways of risk by scientists, managers, stakeholders, and engineers and could help develop a complete environmental management plan for a sustainable seabed mineral extraction. The Bow-tie analysis in this context represents a tool where environmental risk knowledge is translated into mitigation in environmental management.

5.1.2 Sediment plumes

To obtain relevant data for the risk evaluation of the deep-sea environment, it is crucial to investigate the particles to be generated and introduced to the environment. There are several concerns to address when it comes to particles: their size, shape, leaching potential, and sedimentation kinetics. It is important to understand how the redox potential changes after the release of metals, how thick will the layer of sedimented particles be, and how it will affect the biota in relation to natural pelagic sediments. Since the SMS mining particle sizes and shapes are unknown prior to the activity, it is difficult to conduct exposure studies that would provide relevant data. Experiments with finely crushed particles would, in this case, allow comparison with other exposure studies with on-land mine tailings. As the thickness of the expected sedimentation is also uncertain, the commonly used 6.3 millimetres sedimentation thickness in relation to drill cuttings from oil installations can be considered as a starting point, and thinner and thicker layers should be examined to provide data for different groups of organisms (Moodley, 2020).

(Washburn et al., 2019) examined the vulnerability of pelagic and benthic habitats associated with the DSM. The survey showed that both benthic and pelagic habitats were vulnerable to plumes generated during mining activity, but the degree of vulnerability varied with specific risk sources from different types of plumes. The study also concluded that there is a need for site-specific baseline studies and monitoring methods (Washburn et al., 2019). To assess the ecological impact and risk of SMS mining on the seafloor, knowledge about the effects on sediment ecological functioning and key benthic species should be gained. To do so, a range of different kinds of effect endpoints, including mortality and sublethal effects, could be used in different exposure studies with the protozoan, sponge, and blue mussels to provide combined information both to understand and quantify the ecological risk related to effects of SMS exposures. Also, for the sediment community exposure studies, stable isotope labelled tracer organic matter should be added together with SMS tailings. This would provide information on survival and functioning by measuring ^{13}C-enrichment in the different biotic component's bulk tissues after the uptake and ^{13}C-enrichment in the CO_2, indicating community metabolism (Ahnert & Borowski, 2000; Moodley, 2020).

Currently, the predictions of sediment plume size and dispersion are based on various small-scale disturbance experiments and computer models, which are difficult to compare due to distinct underlying assumptions. There is, however, no true data available on plume generation and dispersal by remotely operated machinery in the deep sea. This limits the impact predictions that can be made for deep-sea species and habitats (Chin & Hari, 2020). Plumes are expected to negatively affect ecosystems in all three mining target environments, but they may be especially harmful in nodule provinces due to clear bottom waters and thus very sensitive fauna. However, without a better understanding of the sediment plume properties and sediment tolerances of fauna, the spatial scale of impact is unclear (Amon et al., 2022). Research is yet to be conducted on the exposure, survival, and recovery of deep-sea species in relation to levels of sedimentation expected from SMS mining. Results of this can be compared to estimates of sediment plumes expected from specific technical solutions, and it has also been suggested that they can be used to set goals for new SMS mining technology development (S. Sanni and W. Sognes personal communication, 29 May 2022, see also 5.1.7 Mitigation strategies).

5.1.3 Contaminant release and toxicity

Deep-sea minerals are composed of various chemical elements which may potentially be toxic when released into the water during different stages of the mining process (Gjerde et al., 2016). The toxicity of metals depends on bioavailability - the free metal ions are the most bioavailable. The bioavailability, in turn, is dependent on the water properties (pH, alkalinity, organic material) and the chemical properties of each metal. Ramirez-Llodra et al. (2015) suggest that due to the complex bioavailability of the metals, no general limit values can be used - the toxicity tests should be performed for every single case of mineral mining. Furthermore, it is important to note that the mineral ore is composed of a mixture of metals and chemicals. Therefore, the effects will most likely be different for each individual element.

The release of chemicals will likely occur in the mining of all three mineral resources (massive sulfides, nodules, and crusts) and impact the water properties in target environments. However, mining of SMS deposits is expected to have greater potential for metal toxicity than mining nodules or crusts due to a high oxidation potential of sulfide minerals compared to fully oxidized polymetallic crusts and nodule material. Higher metal concentration in the water may reduce levels of available oxygen and result in sublethal and lethal effects in pelagic and benthic organisms (Amon et al., 2022). Toxic metals could affect not only benthic fauna but also surface-dwelling and mid-water species, as chemicals can be transported to surface waters through upwelling. In surface waters, toxins could easily be taken up by plankton and passed along the food chain posing a risk to entire marine fauna (Chin & Hari, 2020). However, there is no available information on the bioaccumulation and toxicity of metals for marine surface food webs (Chin & Hari, 2020). The technology for assessing toxicity and its effects on deep-sea species is under development, meaning that the impact of toxins on deep-sea fauna is still poorly known (Amon et al., 2022). Some researchers state that toxicity levels and thresholds of DSM are impossible to predict – the impacts should be considered for every single mining case (Gjerde et al., 2016).

5.1.4 Noise and light pollution

It is suggested in the literature that the noise and light pollution originating from mining equipment, infrastructure and surface support vessels would affect the seabed, sea surface, and possibly mid-water depths posing various negative effects on a wide range of species (Chin & Hari, 2020). However, up to now, there is little knowledge about how noise and light pollution may impact marine environments from the sea surface to the seafloor. Due to the deficiency of baseline knowledge and information on specific mining technology, particularly large knowledge gaps are associated with noise from mining activities in the SOFAR channel and impacts of artificial light in deep-scattering layers (Amon et al., 2022). It may be reasonable to suspect that in the SOFAR channel, the noise from mining activity may interrupt whale communication and spread to particularly faraway locations, thus having an impact many kilometres away from the original source. Sound transmission could also deflect to shallower water levels in the vicinity of islands and coasts. SMS mining may assumably not take place directly in the depths of the SOFAR channel, but the deflection of sound into the channel must be considered. Hence, it seems reasonable to recommend it be evaluated case by case and included in the general ERA framework for SMS mining. Due to the limited knowledge, the researchers state that the remediation of possible environmental impacts associated with noise and light pollution is quite unrealistic, and neither is it likely to compensate for impacts by biodiversity offsetting (Chin & Hari, 2020).

5.1.5 Mine waste

Any mining activity produces large volumes of waste, which also often includes chemicals used for processing. Due to the potential toxicity and large volumes of mine tailings, mine waste management is one of the most important environmental issues to be addressed in an ERA (Ramirez-Llodra et al., 2015). Researchers have estimated that an area of around 9000 square kilometres would be impacted by a mining operation of approx. 20 years. Jak et al. (2014) assumed that SMS extraction could produce 40,000 tonnes of water containing 6,000 tonnes of dry solids per day, but there is no research indicating the amount of produced suspended sediment or methods for mine waste treatment and release. Even though the composition of tailings from mining SMS deposits is likely to differ from terrestrial mines, examples of land-based mine waste discharges and impacts may still be instructive (Chin & Hari, 2020). The tailings disposal from land-based mines into the deep-sea has been shown to travel several tens of kilometres and cover large areas resulting in alteration of the sediment and seabed life (Hughes et al., 2015; Ramirez-Llodra et al., 2015).

When developing DSM management options, considerations regarding mine waste disposal are important. It is known that deep-sea ecosystems have distinct characteristics, even though they are often less studied than shallow-water ecosystems. Compared to shallow-water ecosystems, they respond differently to impact and have different recovery potentials (Ramirez-Llodra et al., 2015). Due to the differences in depth of discharge, the discharge rate and oceanographic characteristics for different SMS-rich locations, site-specific studies for each individual mining operation should be required. This should also be addressed when determining the significance of the impact and whether environmental management tools would be effective (Chin & Hari, 2020).

5.1.6 Other hazards

The relevance, importance, and priority of hazards listed in Table 1 but not included in the discussions above are questionable for SMS mining due to the limited available literature and experimental data. These hazards can be grouped into two categories: scale-dependent and knowledge/uncertainty-dependent.

Scale-dependent hazards

The importance of some hazards and potential effects highly depends on the size of the area targeted for SMS mining. From the list presented in Table 1, the following hazards are considered scale-dependent: sludge production; seismic surveys; impacts from mining gear on the deep-sea geology; alteration of abiotic conditions and carbon storage; removal of substrate, ambient water and benthic fauna; impacts associated with the closure of the activity. Assuming that the area is not too large (the criteria are not fully developed), these hazards may be less important for SMS mining than for manganese nodules that cover much larger areas.

Knowledge/uncertainty-dependent hazards

Due to the large knowledge gaps in deep-sea ecology and technological uncertainties associated with the excavation of minerals, many of the hazards are considered to be of lesser importance and relevance for SMS mining. These seem to be: contamination of water with microplastics; generation of sulfuric acid; ocean acidification; accumulation of particles, heavy metals, and chemicals in the food chain; introduction of alien species or pathogenic material; loss of unknown deep-sea fauna; effects on marine mammals and effects on other industries. However, this is a current subjective judgement, and it is questionable which of these hazards one should prioritize to focus on in the future and what kind of knowledge we need to determine the potential impacts and risks?

Since the uncertainties constitute parts of environmental risks, clarifying new knowledge can contribute to reducing environmental risks, and one can thus consider this as a part of mitigation strategies (see further section 5.1.7).

5.1.7 Mitigation strategies

Mitigation refers to measures that can be taken to reduce the probability of an event or lessen the severity of potentially harmful effects (Gjerde et al., 2016). In the context of DSM, the general priority is to conserve biodiversity and ecosystem services. The focus should lie in minimizing the disturbance of the ecosystem and ensuring restoration potential for altered or disrupted vent habitats. Gjerde et al. (2016) suggest that for the industry and regulators, it mainly means:

- Limiting the directly mined area within a region to a level that does not threaten ecosystem integrity; and
- Limiting the size of the area that is affected by secondary impacts (e.g. from plumes and sediment deposition) outside of the mined area by managing the disturbance of sediment. (Gjerde et al., 2016, p. 21)

However, since the mining technology is still under development, it is hard to predict the environmental performance and severity of potential risks that should be addressed in environmental management planning (Gjerde et al., 2016). Several publications address the potential risk factors (Ahnert & Borowski, 2000; Boschen et al., 2013; Clark et al., 2013; Weaver et al., 2018; World Bank, 2017), and a number of scientists mention knowledge gaps that need to be filled in order to inform environmental management (Amon et al., 2022; Billett et al., 2019; Miller et al., 2018). It is difficult to design mitigation measures that would succeed in protecting the deep-sea ecosystems due to their temporal and spatial variability. Especially for SMS mining, present knowledge about the species distribution in time and space is too scarce. More experimental data should be gathered to predict recolonization potential and community composition and settlement (Gjerde et al., 2016).

The main two unavoidable impacts of SMS mining are the loss of fauna in the area of and near the mining site and the harmful effects posed by the potentially toxic sediment plumes. Considering biodiversity, the most important is to ensure effective recolonization of mining-impacted areas and preserve communities that have not been disturbed. Regarding the mitigation of harmful effects posed by exposure to toxic sediment plumes, the focus should lie on minimizing the escape of suspended material during processing and thus reducing the volume of the plume. This may be achieved by improving mining technology and mining procedures to reduce the size, concentration, and, thus, the toxicity of the particles (Boschen et al., 2013). However, how far the sediment plume would extend from the mining site is governed by prevailing hydrography and particle sinking velocity. The possible oxidation of metals and organics in the plume could lead to enhanced oxygen consumption and toxicity in the water column. In addition, depending on the thickness of deposited sediment, the seabed communities may be exposed to clogging or burial (Moodley, 2020). These aspects may be examined in a laboratory and validated with *in situ* experiments in the field to clarify the extent of harmful effects and help develop technology for effective excavation and collection of SMS cuttings.

6 Conclusion

Extraction of SMS deposits is an activity that does not yet take place – methods and technology for realistic implementation of such activities have not yet been procured or tested, which makes it difficult to assess the environmental effects by experience. However, the mining of mineral resources and the associated disposal of waste materials are the major potential sources of environmental hazards for deep-sea ecosystems. Many deep-sea habitats are highly diverse, and the knowledge about the biology and ecology of the wide range of species they support is still scarce. Recently discovered deep-sea species are typically highly specialized, relatively slow-growing, and long-lived. The biological processes are generally considered to be slow, and recovery of the communities requires more time than in a typical shallow water environment. These traits make them particularly sensitive to environmental changes. Thus, the investigations of the potential impact of SMS mining on deep-sea communities should be studied well in advance of the industrial operations (Ahnert & Borowski, 2000; Chin & Hari, 2020).

The Norwegian Environment Agency points out that the large knowledge gaps in geology, biology and technological methods limit the prerequisites for determining the environmental consequences of DSM (Miljødirektoratet, 2021). Different kinds of environmental assessments, along with laboratory testing, are required to obtain key data on ridge mining-specific features (Moodley, 2020). Environmental effect assessment requires knowledge and understanding of the environmental conditions that can be affected regarding habitat types, organisms, and ecosystems in the area, as well as the vulnerability to the possible impacts. It is thus very important that the lack of knowledge, uncertainty, and limitations become clear in the ERA and that all relevant impacts of prospecting, exploration, and exploitation of the activity are included. This is important information for assessing whether the knowledge base is sufficient for decisions to be made (Miljødirektoratet, 2021).

The potential hazards identified in this thesis, associated consequences and other environmental management factors should be considered in the development of an ERA framework for SMS mining activities. Despite the current knowledge limitations, some of the hazards (sediment plumes, contaminant release and toxicity, noise and light pollution and mine waste) seem to be of great importance and should clearly be included in an ERA framework. However, the importance, relevance, and priority of the remaining hazards for SMS mining should be verified once knowledge gaps are filled, and the mining technology is developed. It is still uncertain whether the scale-dependent and knowledge-dependent hazards will be relevant for the future ERA – it is a real challenge to predict the severity of impacts and possible changes in the seabed. To minimize ecological footprint and develop a sustainable seabed mineral mining industry, comprehensive surveys and studies on benthic habitats of potential mining sites and surrounding areas should be conducted to provide information on evolution, community ecology, and adaptation to extreme environments (Clark et al., 2013; Moodley, 2020). Risk should be characterized based on an assessment of exposure to the stressors and the resulting ecological and toxicological effects. This requires analyses of the toxicity due to metals and the physical effect of particles in the plumes, as well as the impact on the water column and sediment ecological functioning in adjacent habitats (Moodley, 2020). Most of the basic information used for the development of ERA is generated in laboratory experiments, but environmental impact studies on a larger scale are necessary for the extrapolation of ecological effects to full-scale mining.

The Bow-tie type of analysis seems to be a very fruitful method to integrate ERA information with environmental management aspects of deep-sea SMS mining. It allows cascading events to create links to external consequences, providing a broader range of the causal pathways of risk. This can yield a good structure for defining and planning mitigation measures related to SMS activities.

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