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Deep Seabed Mining: A Note on Some Potentials and Risks to the Sustainable Mineral Extraction from the Oceans

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Abstract: The rapidly increasing global populations and socio-economic development in the Global South have resulted in rising demand for natural resources. There are many plans for harvesting natural resources from the ocean floor, especially rare metals and minerals. However, if proper care is not taken, there is substantial potential for long-lasting and even irreversible physical and environmental impacts on the deep-sea ecosystems, including on biodiversity and ecosystem functioning. This paper reviews the literature on some potentials and risks to deep seabed mining (DSM), outlining its legal aspects and environmental impacts. It presents two case studies that describe the environmental risks related to this exploitative process. They include significant disturbance of the seabed, light and noise pollution, the creation of plumes, and negative impacts on the surface, benthic, and meso- and bathypelagic zones. The study suggests some of the issues interested companies should consider in preventing the potential physical and environmental damages DSM may cause. Sustainable mining and the use of minerals are vital in meeting various industrial demands.

Keywords: mining; deep-sea; sustainability; minerals; exploitation; potentials; risks; environment

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1. Introduction

As the global population is forecasted to rise to almost 10 billion people by 2030 and 11 billion by 2050, the demand for minerals will follow a similar trend [1]. In addition, the changing consumption patterns in the developing world will further impact the global demand for all resources, including minerals. There is a growing demand for strategic metals such as cobalt, nickel, copper, and manganese because their terrestrial reserves are fast depleting [2,3]. Although some lab-based alloys can substitute minerals used by industries, this has limitations regarding capacity and quality, so mining activities will inevitably continue. Land-based mineral ores have been used to satisfy this demand in the past.

However, several countries have started restricting mining activities using cheap techniques that show no concern for environmental or human health. As these countries try to prevent or even stop permitting these ill mining practices, coupled with the increase in demand, the interest to use deep seabed minerals has become more attractive [4]. The Sustainable Development Goal (SDG) 12 targets clean manufacturing and the sustainable use of minerals to meet various industrial demands [5]. At present, almost all mineral resources are extracted from terrestrial ore deposits. However, high-capacity and high-quality ore deposits are becoming arduous to unearth, so the search expands to the deep seabed as an alternative for low-grade mining. Island countries occupy the deep-sea area within their territorial waters and Exclusive Economic Zones (EEZ), which is an area that sovereign states have special rights to explore and use its marine resources [6].

The deep seabed is generally an area 200 m below sea level. It largely lies outside the limits of coastal countries' continental shelf, defined as a section of a continent submerged beneath a shallow water area called a shelf sea. However, depending on the national coastline, it can also be within a continental shelf, especially in countries that have extended their EEZ. It is regulated by the 1982 UN Convention on the Law of the Sea (UNCLOS), called the "Constitution for the oceans" [6]. This Convention is the basis for different rights and obligations concerning the oceans' uses, such as navigation, construction of pipelines and submarine cables, and national jurisdiction over coastal areas. Based on the Convention, institutions facilitating its implementation (the Commission on the Limits of the Continental Shelf, located in New York) and enforcement (The International Tribunal for the Law of the Sea located in Hamburg, Germany) were established. This legal system facilitates the peaceful settling of disputes and the protection of the oceanic environment and ecosystems.

The deep seabed, also called "the area", is described in the Convention as "the seabed and ocean floor and subsoil thereof, beyond the limits of national jurisdiction." The Convention was signed by almost 200 countries, of which 168 have already ratified it, meaning that the obligations and rights established there apply to them [7]. For the regions classified as continental shelves, which correspond to approximately 56% of the oceans, coastal states can develop their own rules. It is worth noting that state regulations are expected to be at least as strict as international regulations. The international seabed corresponds to approximately 44% of the oceans.

The Convention was the basis for establishing the International Seabed Authority (ISA) or "the Authority." The Authority became operational in 1994 when the Convention came into force (12 months after its 60th ratification, according to article 308) [8]. This institution aims to regulate activities in the deep seabed to prevent damage to ecosystems and biodiversity and even the economic advantages of seabed exploitation. The Authority has been working on a draft mining code to cover environmental, administrative, and financial aspects with a targeted deadline of 2020 for it to come into effect [8].

Article 136 of the Convention indicates that the main objective of the deep seabed mining (DSM) code is regulating the exploitation and development of mineral resources, which are the "common heritage of mankind" [7]. The code means "the whole of the comprehensive set of rules, regulations, and procedures issued by ISA to regulate prospecting, exploration, and exploitation of marine minerals in the international seabed Area" [8]. The Authority has issued 30 multi-year exploration permits, covering 1.3 million km^2, or 0.7% of "the area".

Those permits take the form of contracts, which establish the specific rights and obligations to the companies undertaking those activities. For a company to sign such a contract, it has to be supported by the ISA member of which the company is a national (article 4, of Annex III to the Convention). The supporting country then acts in the role of "sponsoring state". The sponsoring state is responsible for taking all necessary and appropriate measures to ensure that the sponsored companies comply with their contractual duties, with ISA regulations and with obligations arising from the Convention, such as protecting the marine environment and human life. Failure to take those measures means that those sponsoring states may also be liable for any damages which may occur [8].

However, no commercial mining activities so far occur, although DSM has been envisioned since the 1960s when the potential of extracting minerals and other resources from the seabed started to be noticed. This emergent industry took many years to develop due to three main factors:

- The limited availability of technology.
- The cost–benefit dilemma which makes the high-cost investments quite risky: it is a fact that deep seabed research has high costs.
- The potential and expected environmental impacts [9].

Currently, DSM targets three main metallic resources: polymetallic (manganese) nodules (PMN), seafloor massive sulphides (SMS), and cobalt-rich crusts (CRC) [10,11]. These resources comprise significant concentrations of copper, cobalt, nickel, iron and manganese hydroxides and trace concentrations of rare earth elements. These mineral-rich ores range from 400 m to 7000 m. The most attractive mining sources in terms of raw materials are the SMS, formed by the mineral-rich hot water rising to the seabed, meeting cold water, and forming rich crusts (active or recently active hydrothermal vents). The vent ecosystems are very delicate and short-lived systems. They do not form over millions of years but rather over decades, depending on whether they are located on low-spreading or fast-spreading seafloor. The SMS are more attractive resources because they have higher grades of minerals compared to PMN and CRC. They also have a few or no overburden to be removed. In addition, their extraction technology is adaptable from that employed in deep-sea oil operations [12]. Currently, there is an increasing focus on nodules. As of 2018, there are 300 proven sites, with more than half of them described as rich crusts attractive for commercial use [9]. However, being rich with the greatly demanded minerals, these sites possess very delicate ecosystems, and mining activities will significantly affect these sites formed over millions of years [13]. While much research still has to be carried out to obtain a proper picture of the distribution of vulnerable deep-sea ecosystems, precaution should be the basis of any policy due to the distribution of the vulnerable ecosystems, their resilience, as well as their impact on, e.g., food chains [14,15].

Details of the mining operations are critical in understanding the extension of the impact on these ecosystems. However, equipment and technologies are still under development. Current technology utilizes a self-propelled mining machine that buffers the top layer of sediments, including nodules, via a flexible pipe that transports them to a mining vessel on the surface. These nodules are sorted, and then waste sediment is discharged back into the water to a determined depth. On the other hand, the metallic resources are excavated by a continuous mining and off-loading operation for further processing at other sites [16]. The process seems straightforward. However, a crawler as an SMS mining machine has many design aspects based on the properties of an expected, irregular seabed soil, the depth-related pressure variables, and others. These properties all affect the optimal design and operation, resulting in trade-offs between constraints and overall operation efficiency [17].

This article, therefore, reviews the legal aspects of DSM and the environmental risks it poses. Two case studies are used to illustrate such risks. The paper's contribution is synthesizing key insights offered by existing studies related to the environmental risks of DSM. It also suggests key issues miners will need to consider to lower the environmental effects of DSM significantly.

2. The Legal Aspects of DSM

Human interest in mineral extraction from the deep sea has been increasing ever since discovering metals and minerals through 1870s expeditions [18]. However, interest in DSM has not started before the 1960s. While the creation of the ISA is a step towards management of deep seabed minerals, it faces many challenges regarding management of global commons. Different innovations need to be introduced, related to empowering Less Developed Countries, moratoria, but in particular increasing the role for international law [19]. Besides issues with jurisdiction, enforcement, etc., important international DSM players, such as the USA, are not members of the ISA (although some attend the ISA meetings and do have mining company subsidiaries in other countries that are members), which could undermine the efforts toward lowering the potential risks of DSM, given that non-members do not influence the decisions of the ISA as much as members. However, while non-members and observer organizations such as research institutes or NGOs do not vote, they may have a voice on important matters such as promoting the sustainable use of DSM resources and research collaboration (according to Article 75, the Rules of Procedure of the ISA Council).

The ISA rules regarding mineral resource exploration: 2000 (polymetallic nodules), 2010 (polymetallic sulphides), and 2012 (cobalt-rich ferromanganese crusts) are significant for the sustainability of DSM. In total, 30 exploration contracts in the Area have been signed with either individual firms or joint ventures [8]. Each contract must be supported by an ISA member (as a "sponsoring State") for monitoring responsibilities. The ISA can limit withdrawal rights due to damages to the seabed or marine biodiversity (Article 145 of the 1982 Convention) [8].

The 1982 Convention, coming into force in 1994, resulted from 11 sessions held from 1973 to 1982 [20]. While it does cover the negative impacts of deep-sea mining, many related issues are not considered. Apart from the ISA, other international laws are relevant to DSM. For example, the multilateral agreement of the G7 summit might be a powerful legal and political action to the ISA. The 2015 G7 summit hosted by Germany requested that the ISA should work on a clear, effective, and transparent code for sustainable DSM. In 2017, the United Nations drafted a treaty regarding the conservation and sustainable use of marine biodiversity [21]. In September 2018, the intergovernmental conference held one organizational and three substantive meetings to prepare a draft of an international legally binding instrument. The fourth and last meeting was supposed to occur in March 2020 but was postponed to August 2021 due to the ongoing COVID-19 pandemic. Creating new international rules is a time-consuming process, which creates challenges such as the need to solve jurisdictional, legal, and technological issues [22]. There are jurisdictional challenges and cumulative impacts of other international activities such as deep-sea mine tailings and fisheries.

Another important development was adopting a resolution by the European Parliament in 2018 [23]. The European Commission was called on to encourage EU countries to cease sponsoring ISA contractors and stop deep-sea mining on their continental shelves. According to this resolution, the precautionary principle would be applied. A moratorium on commercial DSM would apply if there were some proofs of serious, irreversible damage. However, this resolution is not binding, and no impact on the sponsoring of ISA contracts has been observed until now, further buttressing the need to review the potential environmental impacts of DSM.

3. Materials and Method

The desktop study research approach was employed to review and synthesize key insights offered by existing studies on the environmental risks of DSM. The approach consists of the following three main components:

1. A review of the literature on the general environmental impacts of DSM.
2. A description of the specific impacts at the various levels of marine ecosystems.

3. An analysis of a set of case studies from DSM projects illustrating some of the projects being pursued in specific geographical regions and their potential environmental impacts.

Literature from secondary sources about the general environmental impacts of DSM, including academic (journal articles, books) and gray (reports, maps, and agency websites) documents, was identified and gathered. Articles published since the year 2000 were considered since that was the beginning of ISA regulations. The Web of Science, Scopus, and Google Scholar databases were used to search and identify relevant literature. The rationale for using these databases is that they are comprehensive and widely used in academic research. Keywords such as deep seabed, ocean floor mining, environmental impacts/risks, marine ecosystem, and mining projects guided the researchers in identifying relevant literature. Two case studies of DSM were selected so that one (Patania II) is located within the "Area", and the other case of seabed mining (Solwara I) is outside the Area.

The literature was analyzed through three stages: (a) organizing the literature according to the research's components mentioned above; (b) a thorough iterative search of the literature to generate themes addressing the study objective; (c) summarizing and synthesizing the themes [24]. The results of the analyses and the case studies are presented in the following section.

4. Results: The Environmental Risks Related to DSM

Mining the deep seabed for minerals in different habitats, such as the abyssal plains (PMN), hydrothermal vents (SMS), and seamounts (CRC), has been planned [16]. Since the 1970s, several governments and companies began to pursue DSM within their exclusive economic zones and continental shelves as well as in "the area" [25]. Examples for DSM mining operations and explorations are provided in Table 1. Technological setbacks, difficult international negotiations, and volatile prices for precious metals led to delays, and explorations were even abandoned. For the international waters, the ISA has granted about 30 exploration contracts, and several other activities are ongoing in EEZ and on continental shelves [5,9,26,27]. Except for the exploratory tests, no commercial deep-sea mining activities are fully taking place yet.

Table 1. DSM operations on Continental Shelves and "the area" [16,28].

Resource	Location	Contract Holder/Country
Seabed mining operations on continental shelves		
SMS	Bismarck Sea, PNG	Nautilus Minerals Inc. (Canada), now acquired by Deep Sea Mining Finance Limited
	(Solwara I Project)	Diamond Fields International (Canada)
	Atlantis II Basin (metalliferous sediments in brine pools), Red Sea	Bluewater Minerals (Solomon Islands) Ltd. (Solomon Islands)
Diamonds	Namibia continental shelf	Diamond Fields (Namibia)
Iron ore sands	South Taranaki Bight, west coast of North Island, New Zealand	Trans-Tasman Resources (New Zealand)
	Westland sands, Ross to Karamea, west coast of South Island, New Zealand	Trans-Tasman Resources (New Zealand)
Phosphorites	Chatham Rise, east side, South Island, New Zealand	Chatham Rock Phosphate (New Zealand)
	Western Cape, South Africa	Diamond Fields (South Africa)
	Groen River to Cape Town, South Africa	Green Flash Trading 251 (South Africa)
	Cape Town to Cape Infanta, South Africa	Green Flash Trading 257 (South Africa)
	Sandpiper Marine Phosphate Project, Walvis Bay, Namibia	Namibian Marine Phosphate (Pty) Ltd. (Namibia)

Table 1. *Cont.*

Resource	Location	Contract Holder/Country
	Exploration contracts in the Area approved by the ISA	
PMN	Clarion Clipperton Zones of the Pacific Ocean (CCZ)	China Minmetals Corporation (China) Cook Islands Investment Corporation (Cook Islands) UK Seabed Resources Ltd. (UK) Ocean Mineral Singapore Pte Ltd. (Singapore company majority-owned by Keppel Corporation, Minority shareholders: Seabed Resources Ltd. (Lockheed Martin UK Holdings Ltd.); Singapore-based Lion City Capital Partners Pte. Ltd.) G-Tec Sea Minerals Resources NV (Belgium) Marawa Research and Exploration Ltd. (Republic of Kiribati) Tonga Offshore Mining Limited (A subsidiary of Nautilus Minerals Inc.) Nauru Ocean Resources Inc. (Republic of Nauru) Federal Institute for Geosciences and Natural Resources of Germany IFREMER Institut (Institut français de recherche pour l'exploitation de la mer.) (France) China Ocean Mineral Resources Research and Development Association Government of the Republic of Korea JSC Yuzhmorgeologiya (Russia) Interoceanmetal Joint Organization (different nations) (Governments of Bulgaria, Cuba, Czech Republic, Poland, Russian Federation, and Slovakia.) Deep Ocean Resources Development Co. Ltd. Global Sea Mineral Resources NV
	Indian Ocean	Government of India
	Western Pacific Ocean	Beijing Pioneer Hi-Tech Development Corporation
SMS	Central Indian Ocean Mid-Atlantic Ridge Central Indian Ridge Mid-Atlantic Ridge	Government of India BGR (Federal Institute for Geosciences and Natural Resources of Germany.) of Germany IFREMER Institut (France) Government of the Republic of Korea Government of the Russian Federation Government of the Republic of Poland IFREMER Institut (France)
	Southwest Indian Ridge	China Ocean Mineral Resources Research and Development Association
	Arctic Mid-Ocean Ridge (AMOR)	Norwegian University of Science and Technology (Norway)
CRC	Rio Grande Rise, South Atlantic Ocean Western Pacific Ocean Magellan Mountains/Pacific Ocean	Companhia De Pesquisa de Recursos Minerais (The Geological Survey of Brazil.) Japan Oil, Gas, and Metals National Corporation (JOGMEC) China Ocean Mineral Resources Research and Development Association (COMRA) The Republic of Korea Ministry of Natural Resources and Environment of the Russian Federation

The major activities that cause impacts and environmental issues related to DSM are summarized in Table 2. The first two categorized are activities that cause impacts, which are related to sediments from mining activities and mine tailings, and the toxicity of sediments. The third category consists of the potential impacts on plants and animals. Due to the need to provide a more concrete analysis, two case studies (one on the continental shelf and one in deep waters) were chosen, which describe the scope of both DSM initiatives.

Table 2. Major risk-prone DSM activities and their potential impacts on the environment.

Activities and Environmental Impacts	References
Sediments from mining activities and mine tailings	
Nutrient enrichment	Beaudoin and Baker [29]; Sharma et al. [30]
Masking of sunlight and bioluminescence	Sharma [2]
Alteration of water properties	Hauton et al. [25]; Dover et al. [31]; Peukert et al. [32]
Impact on the mining operation	Miller et al. [20]; Weaver et al. [33]
Oxygen depletion due to organic matter in plumes	Gillard et al., 2019 [34]; Drazen et al. 2020 [35]
Sediment's toxicity	
Sediment toxicity caused by sulfides	Boschen et al. [36]; Collins et al. [37]
Sediment toxicity caused by manganese	Peukert et al. [32]
Sediment toxicity caused by metals	Hauton et al. [25]
Impact on fauna and flora	
Removal of fauna and flora	Peukert et al. [32]; Boschen et al. [36]; Collins et al. [37]; Baker et al. [38]; Jones et al. [39]; Ramirez-Llodra et al. [40]
Burial of organisms, e.g., by re-deposition of plumes	Baker et al. [38]; Jones et al. [39]; Ramirez-Llodra et al. [40]; Glover and Smith [41]
Introduction of new species to the ecosystem	Van Dover [42]; Van Dover et al. [43]
Alteration of substrata	Gollner et al. [44]; Halfar and Fujita [45]
Changes in local currents	Baker et al. [36]; Ramirez-Llodra et al. [40]; Van Dover [42]
Changes in temperature	Gollner et al. [44]
Noise	Baker et al. [36]; Gollner et al. [44]; Gena [46]

4.1. Case Study A: Patania II (Continental Shelf)

Patania II is the provisional name of a pre-prototype collector vehicle that is to be used for DSM of nodules on the seafloor in the Clarion–Clipperton Fracture Zone (CCFZ) shown in Figure 1. The vehicle is intended for scientific projects (e.g., JPO-OII Mining Impact 2 and ProCat #2) to deliver information about the technological feasibility and the likely environmental impacts from mining activities. During the small-scale exploration, nodules are collected from a small seafloor area (about 0.1 km^2) at a water depth of ca. 4400 m, over a few days [47]. The technological objectives are to validate the maneuverability, reliability, and nodule pick-up efficiency of the vehicle and analyze potential environmental impacts. It is challenging to address environmental issues such as the scale of impacts caused by suspended sediment plumes, the resilience and regional connectivity of different deep-sea species, and the effects of disturbances caused by mining on ecosystems and their functions (i.e., benthic food web and biogeochemical processes). This is because Patania II cannot assess regional connectivity, or ecosystem-scale function, which it is not intended to.

Two independent environmental impact statements (EIS) on the vehicle's mining operations have been published recently [47,48], which are the basis for this case study's description. The seabed area associated with polymetallic nodules in the CCFZ, where the small-scale exploration will occur, supports a highly diverse fauna that spreads over small and large spatial zones, but their connectivity is unknown. The potential impacts of nodule collection on biological communities and the physico-chemical environment are related to the following issues [10,26,47].

- Habitat and nodule removal.
- Sediment disturbance and plume formation and deposition caused by the machines hitting the seafloor and sediment plumes re-released in the water column.
- Concentration of plume particles in the water column above the seafloor.
- Biochemical alterations of the sediment (change of habitat integrity).
- The possible discharge of toxic sediments and substances into the lower water column
- Emissions to air, noise, and light pollution.

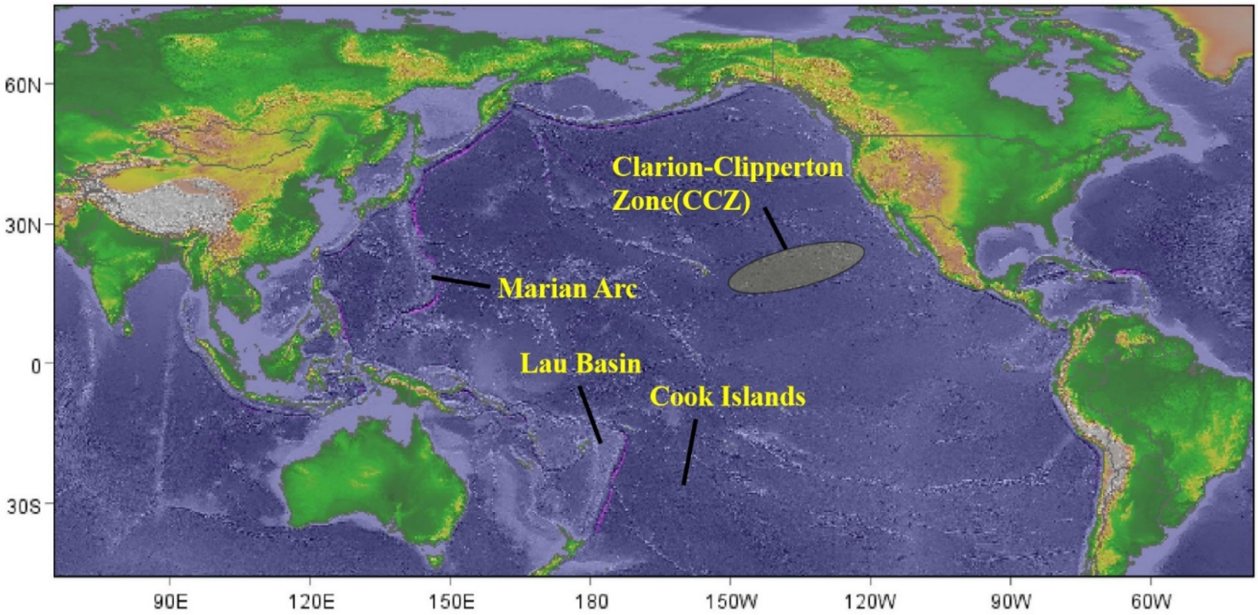

Figure 1. The location of Patania II in the North Pacific Ocean (map created by the authors).

However, as the intervention is a pilot trial, the responsible company claims that no serious damage to the aquatic environment will be caused. The rules around component tests and test mining are the legal aspect of the ISA Exploration Regulations, such as ISBA/19/LTC/8, and more recently ISBA/25/LTC/6.rev1 [8,20]. An overview of the environmental risks related to this project is provided in Table 3, and they are described in more detail in the subsequent sections.

Table 3. Some of the environmental risks of the Patania II project (modified from GSR [47]).

Activity	Event	Potential Environmental Impact
Settling on seafloor and moving	Local disturbance of habitat Compaction of sediment	Seafloor surface structure will change The death of organisms changes species diversity
Collector Head Operation	Removal of habitat	Changes in seafloor surface structure
	Removal of organisms	Death of organisms, changes in abundance, and species diversity
	Plume generation	Smothering of organisms, increased food supply for benthos, reduction of bioluminescence, leading to changes in biodiversity
	Release of metals from sediments into the water column	Trace metal uptake
	The lighting of Patania II, fauna attraction	Some individuals attracted to the suction area may be lost
	Noise and vibration	Local disturbance to fauna
	Hydraulic fluid leaks	Environmental impacts caused by ~0.9 m^3 fluid leaks (assuming total loss from a single machine)
	Failure or technical malfunction, loss of power and/or communications	Patania II tool will be left on the seafloor
Raising/lowering machine to/from a vessel	Fauna attraction during ascent and descent	Entanglement of fauna
Sonar	Noise	Cetacean disturbance
Umbilicals	Entanglement Hazard in the water column	Loss of equipment, production impact Cetacean entanglement

The Patania II project has faced many technical difficulties. Even before the Patania II nodule collector was launched, the five km long cables (“umbilical”) needed to hold the 25 t Patania II vehicle and for communication and power supply were damaged. For security reasons, the launch of Patania II needs to be postponed by several months [48,49].

4.2. Case Study B: Solwara I

The Solwara I project, whose location is shown in Figure 2, was expected to be the world's first large-scale DSM activity [49]. The project's environmental permits (mining lease) and mining license have been granted to Nautilus Minerals and its subsidiary Nautilus Minerals Niugini. However, due to the bankruptcy of the company, all activities were discontinued. The Solwara I site in the Manus Basin of the Bismark Sea, located close to Papua New Guinea (PNG), is well over twenty hydrothermal fields [5]. The fields contain a rich deposit of seafloor massive sulfides (SMS) with base metals, copper, and zinc (Table 4), as well as relatively high grades of gold and silver (i.e., 7% copper in the ore and 6 g gold per ton) [20,46,50].

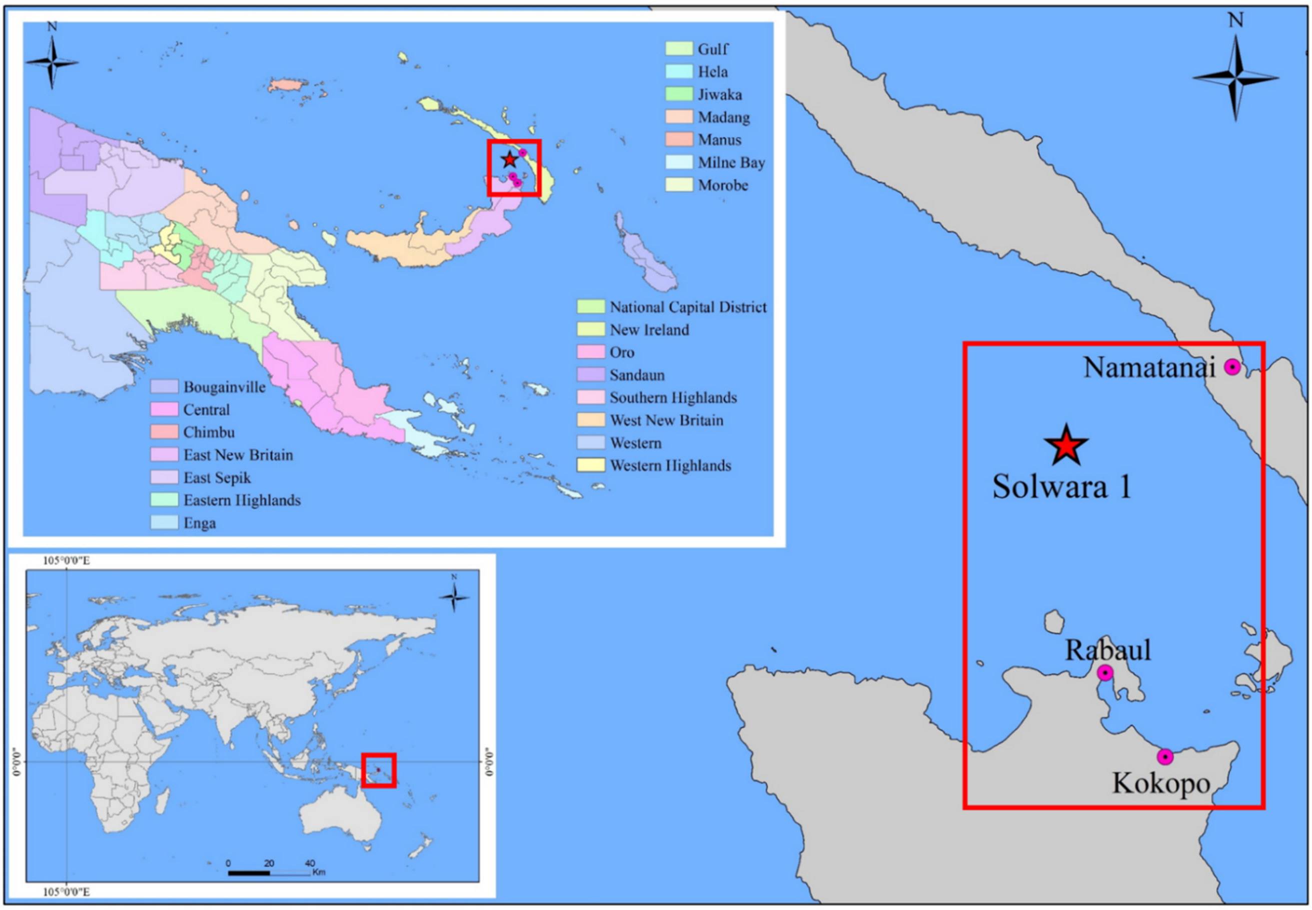

Figure 2. The location of Solwara I in the Bismarck Sea.

Table 4. Indicated and inferred mineral resources for Solwara I [46,51].

Domain	Tonnes	Cu (%)	Au (g/t)	Ag (g/t)	Zn (%)
Massive sulphide (indicated)	870,000	6.8	4.8	23	0.4
Massive sulphide (inferred)	1,300,000	7.3	6.5	28	0.4
Chimney (inferred)	80,000	11	17	170	6
Lithified sediments (inferred)	20,000	4.5	5.2	36	0.6
Total	2,170,000				

The area covered by the Solwara I deposits is about 0.112 square kilometers, and the deposit lies at approximately 1600 m deep. Table 4 indicates that the massive sulfide has a high measure of geological confidence (indicated resource) of about 0.87 Mt and 1.3 Mt based on lower confidence (inferred resources) [13]. In contrast, commercial drilling data indicate a deposit (measured) size of 2.5 Mt [51]. Globally, about 40% of the SMS deposits lie within the EEZ of coastal states [5,12,52].

The deposit has been under scrutiny since 2005. The PNG granted an environmental permit for the site's development for 25 years [5]. In 2011, a mining license for an area covering about 60 square kilometers was awarded to Nautilus Minerals [20]. Due to the nature of the exploration and exploitation activities, the company was requested to formulate an EIS. Based on this, several potentials and project-related environmental impacts have been identified (see Table 5). The potential environmental impacts related to DSM range from site-specific to regional-scale impacts over short and long durations and might not occur in all marine environments. The environments where most impacts are likely to occur include (1) the benthic zone (i.e., seafloor) and (2) the meso- and bathypelagic zones [36].

Table 5. Overview of the environmental issues related to the Solwara I project (summarized from [26,36,53–57]).

Environmental Zone	Potential Environmental Impact
Benthic (seafloor)	Changing seafloor surface structure due to habitat removal Loss of endemic and rare species, habitat loss, decreased biodiversity at different levels such as genetic, species, and phylogenetic. Decreasing seafloor primary production Modifying trophic interactions Smothering of organisms and toxic effects due to sediment plume generation and losing material from riser transfer pipe. Losing adjacent communities due to changing hydrothermal activity. Reduced water quality from hydraulic leaks. The anger of transplanting organisms from one mining site to another
Bathypelagic (>1000 m)	Toxic effects of plumes discharged at depth from dewatering. Losing organisms attracted to the suction area by surface mount lights. Reducing bioluminescence due to plume generation
Mesopelagic (200–1000 m)	Toxic effects on pelagic biota, including bioaccumulation through releasing metals into the water column. Disturbing cetaceans due to noise from mining and vessel equipment
Epipelagic (<200 m)	Nutrient over-supply and heightened productivity due to discharging treated sewage and macerated waste. Toxic effects due to spilling of ore or hazardous material caused by mining surface vessels. The demise of aboriginal animals due to exotic species introduction through ballast water and hulls
Surface	Effects on the air quality due to exhaust gases from vessels and machinery

It was predicted that commercial exploitation activities in Solwara I would get underway in the spring of 2019, but the project faces several technological and economic setbacks [58]. Although Nautilus has made large investments in mining technology and assets, it seems that the financial, social, and reputational risks have been too large to continue successfully. Public concern about the DSM activities has grown over the last years and was expressed by civil society representatives in Papua New Guinea. Recently, Nautilus went bankrupt, has filed for court protection from creditors, and was delisted from the TSX exchange [59]. Deep Sea Mining Finance Limited, which now acquires Nautilus, has started moving Solwara I into commercial production (https://dsmf.im/(accessed on: 5 March 2021)).

5. Discussion

The DSM process has the potential of causing physical and environmental damages to the marine ecosystem. According to Deep Green [60], DSM is dominated by western private mining companies to serve their economic interests while portraying the illusion that the practice is a universal public good. However, the literature and both case studies reviewed in the previous section reveal various significant environmental impacts discussed below.

5.1. Impacts on the Meso- and Bathypelagic Zones and at the Surface

For the so-called midwater, which includes the epipelagic, abyssopelagic, meso- and bathypelagic zones, few significant environmental impacts are expected, as no equipment is deployed in the midwater, but the riser pipe passes through it, and the processing waters could be released there in other operations. On the water surface, potential environmental impacts are related to noise and light from the surface vessels and due to accidental discharges of, for instance, hydraulic oil and waste discharges [56]. In addition, sediment plumes can be re-released in the water column causing sediment disturbance, plume formation and deposit, and toxicating and suffocating aquatic organisms [61].

5.2. Impacts on the Benthic Zone

DSM is likely to cause impacts on the biological, chemical, and physical seafloor environment. The Solwara I site can potentially pose adverse environmental effects through (a) the picking of SMS, leading to changes in the micro-topography of the seafloor surface, (b) the discharging of sediments, and (c) light and noise pollution [62]. All faunal classes, including microorganisms and megafauna, will potentially be affected. Larger and mobile epifaunal organisms, demersal scavengers, and fish will potentially leave the area of impact due to plumes' enhanced particle concentration.

5.3. The Creation of Plumes

Environmental concerns regarding sediment removal and discharges are related to the rapid re-deposition of sediments from the resettling plume, which will create a "blanket" of sediments in areas close to the mining field. Benthic organisms are likely to be buried, and the respiratory surfaces of filter feeders can be clogged. The plumes may contain potentially toxic substances and reduced metals, as well as unstable organic matter causing oxygen depletion. As the re-deposited sediments will have a modified grain-size distribution and low average organic content, they will probably influence organic matter remineralization and nutrient cycling processes [61]. There is also a growing concern about the effects of sediment plumes on the midwater fauna [34].

5.4. Light and Noise Pollution

Light pollution means that light is emitted where no natural light sources occur or where the natural light is much weaker. Lighting from cameras and noise caused by machinery and pumps can be reduced but cannot be fully avoided. Many marine species, such as fish, mammals, and invertebrates, are physiologically sensitive to acoustics and lighting [58], although the stressors' impact is rather unclear. Potential adverse effects of noise on marine species are seen in behavior changes, reduced communication ranges and foraging ability, decreased predator prevention, and habitat avoidance [63]. Lighting may induce temporary blindness or deteriorated bioluminescence functions [64].

5.5. Significant Disturbance of the Seabed

The seabed can be significantly disturbed due to nodule removal and any SMS from DSM, likely leading to a micro-topography change [65]. Such alterations of the seafloor may cause changes in the geological setting and the local hydrodynamic current regime and impact the biological environment's biochemical setting. Disturbing the seabed through waste disposal will also impact marine animal and plant species and biodiversity [66–68].

Other hazards that may affect the water and air quality can be caused by leaks of hydraulic fluids, fuel spills, unexpected equipment malfunctions, and greenhouse gas emissions from operations [69,70]. Several mitigation measures have been suggested that lead to residual impacts that are not considered relevant, resulting in elutriate and toxicity tests. These measures include minimizing sediments' penetration, separating nodules from related sediments and seabed, lifting sediments to the surface, treating tailings before discharge, discharging tailings below oxygen minimum zone, and recycling unwanted materials after metal extraction [2]. Another measure is releasing the wastewater in upper water layers, e.g., below the euphotic zone or below vertical migrator zone. Additionally, some sediment may be re-suspended and may affect the water quality. The same effects can be expected from plumes resulting from discharged wastewater from the dewatering processes [20]. This water will be returned close to the seabed. These plumes may contain materials that have undergone some geochemical changes due to exposure to higher temperatures and oxygen [68]. These changes may affect seafloor biological communities by altering the seawater quality and smothering or even burying filter feeders, especially in areas where sediments potentially settle environments, including propositions, lemmas, and corollaries [69,70].

Developing and implementing monitoring and mitigation measures is significant to reducing the harmful effect of DSM on the marine ecosystem and human health [26,71]. Effective measures include designating "set-aside areas" or refuges, artificial eutrophication, deploying artificial substrates for enhancing faunal survival, frequent monitoring of mining activities, and optimizing the construction of mining machines to lessen plume size on the seabed, toxicity of return plumes, and sediment compression [61,72]. These measures can help to avoid or minimize harming the ecosystem while restoring and maintaining its resilience [73].

6. Conclusions

The issue of DSM is a complex one with increasing importance, as it becomes a more realistic proposition. The potential and expected environmental impacts are significant. Identifying potential environmental impacts and their assessment is still challenging, as with all emerging technologies, given the lack of accurate data and the generally poor understanding of deep-sea ecosystems. Although the magnitude of potential environmental impacts is difficult to describe and assess, it is obvious that severe and irreparable environmental impacts at the mining sites will occur. Examples of adverse environmental impacts, as referred to in this paper, are:

- Immediate elimination of seafloor habitats and animals;
- Releasing suspended sediment plumes;
- Altering substrate and its geochemistry;
- Releasing toxins and contaminants due to extraction and removal processes;
- Noise and light pollution;
- Biodiversity losses caused by DSM activities.

The overall consequences to deep-sea ecosystem functions are not yet well known [74–77]. For instance, nodule ecosystems support a rich and diverse fauna, including sessile and mobile species [63]. The characteristics of benthic faunal communities and environmental and geological parameters show a high variability at local spatial scales. Nodule removal impacts the deep-sea ecosystem in terms of loss of seafloor integrity, alteration of biogeochemical processes of remineralization, reduced productivity of benthic communities, and declining populations and densities of plant and animal species. The disturbances caused by DSM may hence affect various ecosystem compartments and functions, leading to long-lasting impacts [78,79].

This study implies that adequate mechanisms are needed to regulate DSM and minimize its environmental impacts properly. Firstly, while non-Convention members cannot theoretically undertake mining activities in ISA-administered areas, there are limited global enforcement mechanisms to oversee it. The property rights are vested in the countries that are members. The ISA member countries have vested mining interests and are themselves making the regulations they will be beholden to. The system was created not to claim unlimited deep seabed areas, leading to international conflicts. As such, countries should mandate mining companies to guarantee environmental protection and compensation mechanisms in the event of pollution damage. In addition, obligations to conduct environmental impact assessments, according to the International Tribunal rules for the Law of the Sea (ITLOS) [80], for the protection of ecosystems are needed and rely on domestic laws of the investor's country of origin.

Secondly, whenever advances in technology make seabed mining profitable, there would be an incentive for more countries to join ISA. However, it may also give rise to conflicts that may undermine the ISA's functioning and a circumvention of the ITLOS. A future study is required to explore the likelihood of successful restoration in the marine habitats targeted for DSM and how it may impact how DSM moves forward.

Given the width of this topic, this paper cannot cover all the potentials and risks of DSM. Future studies should investigate the likely magnitude of disturbance in future commercial DSM operations, the resilience of deep-sea ecosystems, and how do they relate to the planned operations. There is also the need to study the issue of common heritage, impact/preservation reference zones, and the roles of sponsoring states and contractors, which depend on individual DSM activity, as well as the Japanese pilot mining and the disturbance and recolonization experiment on impacts of DSM in the southeastern Pacific Ocean.

The case studies presented in this paper have shown how vulnerable deep-sea ecosystems are and the many risks that DSM poses. Since the worldwide demand for minerals is growing, there is a pressing need to establish standard environmental impact assessments and ecosystem conservation procedures. Only these procedures can ensure that mining operations in the international seabed area do not lead to catastrophic consequences.

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