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Review

Effects of Migration and Diffusion of Suspended Sediments on the Seabed Environment during Exploitation of Deep-Sea Polymetallic Nodules

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Abstract: With the increase in demand for metal resources, research on deep-sea polymetallic nodule mining has been reinvigorated, but the problem of its environmental impact cannot be ignored. No matter what method is used for mining, it will disturb the surface sediments of the seabed, thereby increasing the concentration of suspended solid particles and metal ions in the water body, changing the properties of the near-bottom water body and sediments, and affecting biological activity and the living environment. Focusing on the ecological and environmental impacts of deep-sea polymetallic nodule mining, taking as our main subject of focus the dynamic changes in sediments, we investigated the environmental impacts of nodule mining and their relationships with each other. On this basis, certain understandings are summarized relating to the ecological and environmental impacts of deep-sea polymetallic nodule mining, based on changes in the engineering geological properties of sediment, and solutions for current research problems are proposed.

Keywords: deep-sea mining; polymetallic nodules; sediments disturbance; seabed environment; migration and diffusion of suspended sediment

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Citation: Fan, Z.; Jia, Y.; Chu, F.; Zhu, X.; Zhu, N.; Li, B.; Quan, Y. Effects of Migration and Diffusion of Suspended Sediments on the Seabed Environment during Exploitation of Deep-Sea Polymetallic Nodules. *Water* **2022**, *14*, 2073. https://doi.org/10.3390/w14132073

Academic Editor: Danny D. Reible

Received: 17 May 2022
Accepted: 25 June 2022
Published: 29 June 2022

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1. Introduction

The ocean occupies 70% of the total area of the earth, and about 10–30% of the seabed is covered by polymetallic nodules, which are rich in iron, cobalt, nickel, copper, titanium and other metal elements. The resource potential of polymetallic nodules in the Pacific Clarion–Clipperton Zone (CCZ) alone is 5–10 times that of global terrestrial reserves [1–3]. These huge metal resources are very important to the development of modern society [4,5]. Since the 1960s, developed countries led by the United States, Germany, and Japan have tried to study deep-sea polymetallic nodules [6–9]. However, due to economic, technical, political, and environmental limitations, among other reasons [5], research on polymetallic nodules has not reached the stage of commercial mining. Even so, polymetallic nodules remain the most promising location for the commercial mining of deep-sea metal resources [4,10,11], and they are the main targets of current deep-sea mining research.

Using the Web of Science core database, we searched the literature collected from 1 January 1990 to 31 December 2021 using the keyword “deep-sea mining”. The results are shown in Figure 1. A total of 1306 articles have been published in the past 31 years, and the overall number of articles published each year has increased with time. The trend for the number of articles published annually can be divided into three stages: The first stage was between 1990 and 2000, when research was at a low point, with an annual publication volume of approximately 10 articles. The second stage was between 2001 and 2016, in which the annual publication volume fluctuated between 20 and 50 articles. The third stage was from 2017 to 2021, during which the annual publication volume increased significantly, between 108 and 209 articles. The total publication volume during this stage was 1.5 times the total number of publications in 1990–2016, marking the renewed interest of researchers in deep-sea mining. All of the published articles could be divided into six categories according to discipline: environment, geology, technology, engineering, oceanography and policy. Environment-related research accounted for the largest proportion, followed by geological research. Over 70% of the articles focused on environmental, geological and mining technology issues related to deep-sea mining.

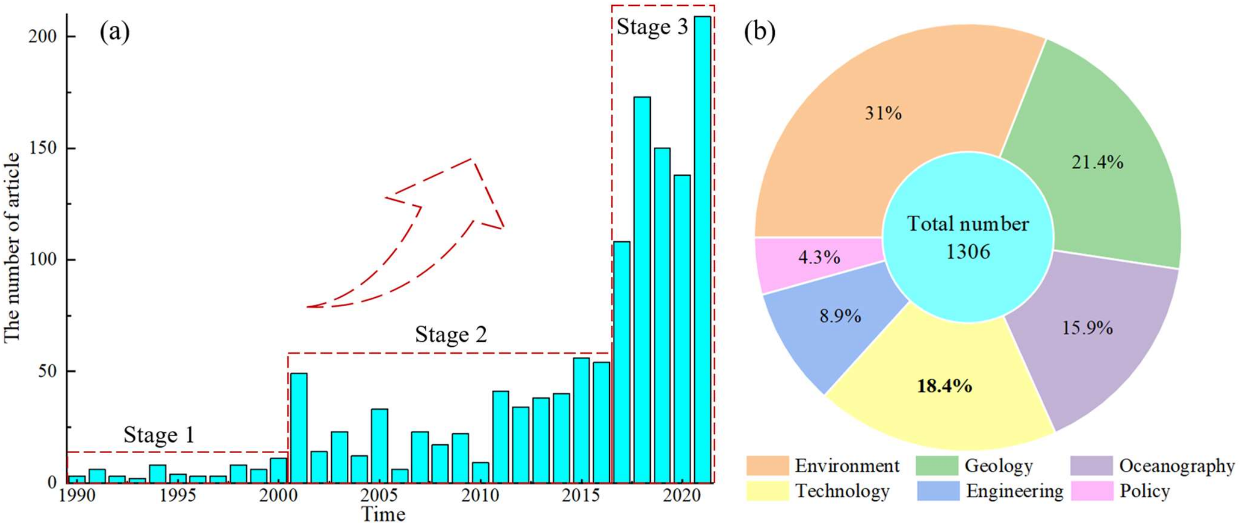

Figure 1. Statistics of articles published between 1990 and 2021. (**a**) The statistics for articles published in different years; (**b**) the proportion of articles published in various disciplines during the past 31 years.

On this basis, we tracked the development trend of the research direction of articles published between 2017 and 2021, as shown in Figure 2. The number of research papers in the environmental direction remained high, accounting for nearly 40% of all research directions. In addition, the number of publications in geology and mining technology decreased year by year, while the number of research papers in oceanography and engineering increased year by year. This means that while attention continues to be paid to the environmental impact of mining, more consideration has been given to the engineering practices of deep-sea mining and the understanding of deep-sea oceanography. Through a deeper understanding of deep-sea oceanography and deep-sea mining engineering, we can better understand the environmental impact of deep-sea mining.

After decades of development, research into deep-sea polymetallic nodules has experienced a peak and decline. There have been great improvements in mining technologies, legal regulations and people's knowledge of the ocean [10]. However, it is undeniable that no matter what mining method we adopt at present [12,13], the environmental impact cannot be ignored [7,14,15]. The environmental impact of polymetallic nodule mining is caused mainly by the processes of collection and tailings discharge [16]. During mining operations, such processes disturb seabed sediments, change the benthos living environment, increase the concentration of solid suspended particles in water, and affect the chemical properties of sea water [17,18]. Studies have also suggested that deep-sea mining can affect the carbon cycle in seabed sediments [19], but most researchers have focused on the impact of deep-sea mining on biology [20–22].

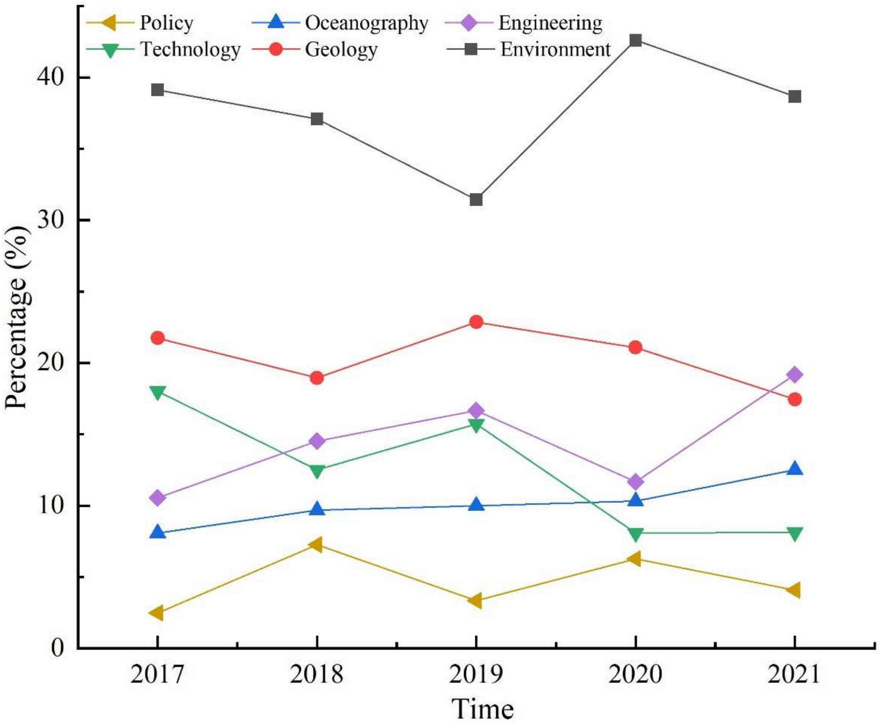

Figure 2. Changes in the proportion of papers published in each research direction from 2017 to 2021.

To better manage the mineral resources in the international seabed area, the International Seabed Authority (ISA) was established in 1982 in accordance with the United Nations Convention on the Law of the Sea, with responsibility for the exploration and development of seabed mineral resources in public waters [23]. So far, the International Seabed Authority has approved 19 exploration contracts for deep-sea polymetallic nodules, and the explorer with the longest exploration time has been conducting resource surveys for more than 20 years. The surveying of resources and reserves has been accompanied by surveys of environmental baselines. The exploration regulations promulgated by ISA in 2000 and the draft development regulations promulgated in 2019 [24], each propose explicit requirements for the surveying and monitoring of the ecological environment in deep-sea exploration areas (physical ocean, chemical oceanography, geological properties, and biomes) [25]. To date, the Belgian Global Sea Mineral Resources (GSR) company has submitted the world's first environmental impact assessment report for deep-sea polymetallic nodules [26], and other countries such as the United Kingdom, Japan, Germany, and South Korea are also actively conducting research on mining-related topics [14,27–29].

These small-scale in situ mining environmental disturbance experiments provide a way for us to better understand the environmental impact of deep-sea polymetallic nodule mining [30], and also to verify the ability of our equipment to work in the deep sea [7]. To address the environmental impact problem, based on investigations of the environmental baseline [31], using the environmental monitoring results from the small-scale mining test, the environmental impact of mining was analyzed and evaluated [19,32]. Therefore, the degree of environmental impact under different mining states and influencing factors has been further defined [33,34], and the environmental impact of polymetallic nodule mining can be more clearly understood [35]. The essence of deep-sea mining is the process of dredging, which is accompanied by dynamic changes in sediments. These dynamic changes in sediments have a direct impact on the environment, so the relationship between the dynamic changes in sediments and environmental impacts during deep-sea mining is very important.

Therefore, this paper focuses on the potential environmental impacts of deep-sea polymetallic nodule mining. First, the basic characteristics, engineering geological conditions and mining methods for deep-sea polymetallic nodules are summarized. Then, the environmental impact of mining activities is summarized from the perspective of the migration and diffusion of resuspended sediments disturbed by mining. We studied sediment disturbance, the diffusion of resuspended sediment in the water body, and the redeposition of the resuspended sediment in the process of ore accumulation, and its impact on the seawater environment including marine organisms. On this basis, the existing deep-sea polymetallic nodule exploration area ecological environment surveying and monitoring technology is considered, along with the environmental impact assessment method. Finally, based on our findings, the overall progress of the current research is summarized, and attention is drawn to the problems facing researchers into deep-sea polymetallic nodule mining from the perspective of dynamic sediment changes.

2. Overview of Deep-Sea Polymetallic Nodules

2.1. Distribution and General Characteristics

Deep-sea polymetallic nodules are generally distributed in abyssal plains with a water depth of 4000–6000 m. Figure 3 shows the global location of deep-sea polymetallic nodule exploration areas and exclusive economic zones. The CCZ is most widely distributed in the eastern Pacific, where the average abundance of polymetallic nodules is approximately 15 kg/m^2 [4]. It is also distributed in the Indian Ocean, Cook Islands, and Peru Basin [3–39], with an average abundance of 5 kg/m^2, 5 kg/m^2, and 10 kg/m^2, respectively [40]. In addition, Figure 3a–d shows the morphological characteristics of polymetallic nodules and their occurrence state on the seafloor. Polymetallic nodules occur on the surface of the seabed, and are mostly spherical, although other shapes exist such as rods, strips, and cauliflowers [41]. The diameter of the nodules is usually between 1 and 20 cm, the density is between 1.7 and 3 g/cm^3, and the burial depth is generally not more than 30 cm, though there also exists a small quantity of polymetallic nodules buried in sediments deeper than 30 cm [42].

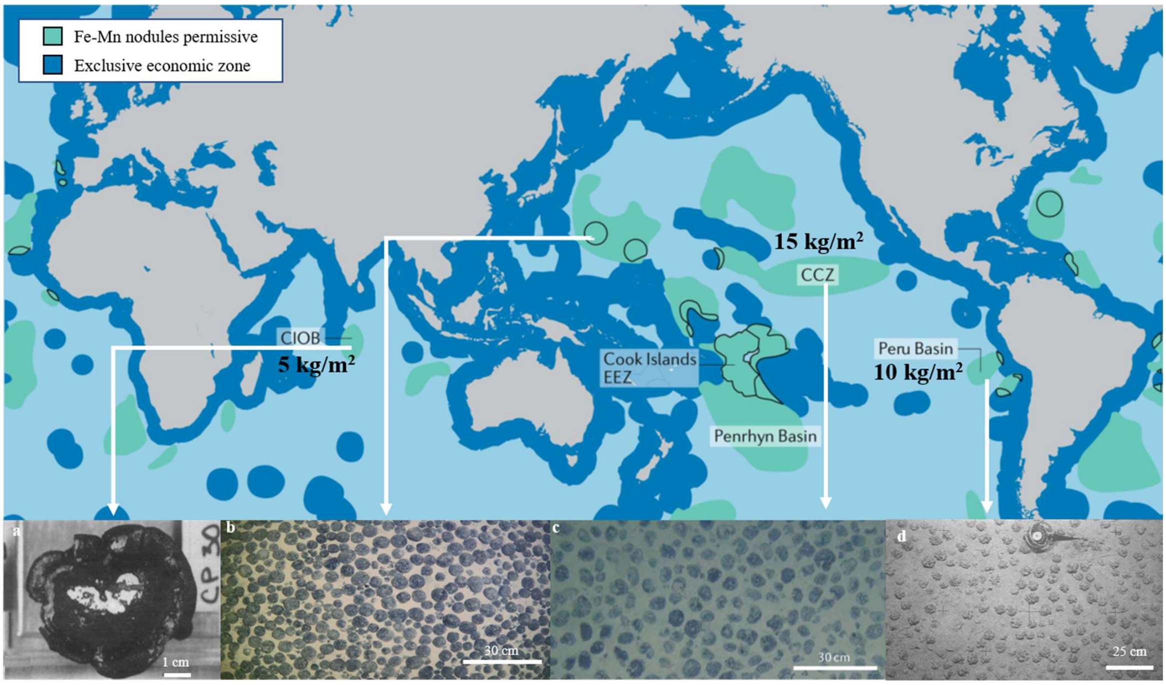

Figure 3. The distribution of deep-sea polymetallic nodules in the world and the occurrence state of nodules in different regions, modified from [4]. (**a**) The state of mixed polymetallic nodules in the Indian Ocean seabed [37]; (**b**) the occurrence state of polymetallic nodules in the Western Pacific Ocean (provided by COMRA); (**c**) the occurrence state of polymetallic nodules on the seabed in the eastern Pacific CCZ [4]; (**d**) the occurrence state of polymetallic nodules in the Peruvian Basin [42].

Previous studies have shown that the difference between buried nodules and those on the surface is mainly reflected in the surrounding redox environment, with some buried nodules displaying obvious dissolution phenomena [43]. The growth rate of deep-sea multigold nodules is approximately 1–10 mm/ma [44], which is about one-thousandth of the rate of oceanic deposition [45–47], but it is interesting that most nodules exist only on the seabed surface. Some studies have suggested that the push action of organisms combined with the shear action of the bottom current causes the sediments on the surface of the nodules to be suspended, so that the nodules always remain at the surface of the seabed [48–50]. Some researchers also believe that the driving force for removing the sediment on the surface of such nodules may result from earthquakes. Millions of earthquakes occur on the ocean floor every year, and the combination of earthquakes and the action of bottom currents may also keep the nodules on the surface of the seabed [46,51]. Some researchers believe that different metallogenic environments make it difficult for buried nodules to be preserved, while nodules on the seabed surface are more suitable for preservation [52]. Environmental claims are similar, but the exact cause is not yet conclusive.

It is generally believed that the metal elements in the nodules mainly come from seawater and sediments, so metallogenic models of nodules are generally divided into three types: hydroform, diagenetic and mixed [43]. Furthermore, topography has a significant impact on the distribution of nodules. In general, nodules are mostly distributed in deep-sea basins and areas with flat terrain. However, the relationship between distribution and micro-topography is not yet clear. Some studies have suggested that when the terrain slope is small, a higher slope indicates a higher abundance of nodules; the latest research suggests that the distribution of deep-sea polymetallic nodules may be related to the distribution of ancient submarine landslides [53]. Research on this issue can not only supplement an understanding of the metallogenic mechanisms of polymetallic nodules, but can also provide a basis for the division of geological units before the commercial mining of nodules in the future. Different engineering geological units have different degrees of reaction in the process of nodule mining, and their optimal mining modes have different degrees of environmental impact. Therefore, the investigation and division of engineering geological conditions in nodule areas is particularly important.

2.2. Geological Engineering Characteristics

The areas in which deep-sea polymetallic nodules occur have large water depth, being generally below the carbonate compensation depth (CCD), and the sediment is mainly composed of siliceous soft clay. The overall terrain is relatively flat, but there are also small seamounts and hills. These small seamounts and hills affect not only the distribution of nodules [53,54], but also the collection paths and the positioning of mine carts during nodule mining. The early division of engineering geological units considered only two basic factors: seabed topography and sediment type. The engineering geological conditions of the exploration area are roughly divided across a large range, but the abundance of nodules, the physical and mechanical properties of sediments, and the hydrodynamic conditions of the seabed have not been considered [55–57]. In addition, the spatial distribution of organisms obeys a certain law, and this law is also related to the distribution of nodules [58–61]. In future commercial mining, the above content will be the basis for the division of engineering geological units and mining units in mining areas. The superficial sediment is in direct contact with the mining vehicle, and its physical and mechanical properties affect the movement of the mining vehicle, and are a key factor affecting the degree of mining disturbance.

The physical and mechanical properties of shallow sediments in different deep-sea regions have been measured, as shown in Table 1. Among them, the sampled water depth in the CCZ and the western Pacific was approximately 4500 m, and the sediment properties were counted at a depth of less than 20 cm. The depth of sampled water in the Peruvian Basin was approximately 4200 m, and the sediment properties were estimated to be shallower than 10 cm from the surface. The sampling depth of the Mariana Trench was 8638 m, and the sediment properties are less than 12 cm into the surface layer. It can be seen that in terms of sediment properties alone, the properties of shallow sediments in different regions are not significantly different, and they all have the characteristics of high water content, high porosity and low shear strength.

Table 1. Physical and mechanical properties of shallow sediments in different polymetallic nodule occurrence areas.

Different Areas.	Water Content (%)	Void Ratio	Internal Friction Angle	Wet Density (g/cm^3)	Shear Strength (kPa)
CCZ [53]	215–284	3.15–3.93	3.9–5.7	1.18–1.49	4.2–6.6
Western Pacific [62]	133–178	5.56–7.21	3.6	1.16–1.38	2.6–7.6
Peru Basin		7–13 [14]		0.29–0.39 [14]	3–5 [63]
Mariana Trench [64]	246.2	6.03	5.384	1.249	

In addition, the properties of superficial sediments also vary with depth. The particle size of sediments shallower than 10 cm in the surface layer is smaller, and approximately 90% of the particles are smaller than 0.02 mm [65]. In addition, the water content of surface sediments is extremely high, generally exceeding 100% [66]. The shear strength of sediments is obviously delaminated. The shear strength of sediments shallower than 10 cm in the surface is generally lower than 2 kPa. Then, with the increase in sediment depth, the shear strength of sediments gradually increases. The shear strength of the sediments changes again at the depth of 20 cm [67], and some studies have suggested that the change here is caused by benthic bioturbation [14,68], which is also consistent with the holes at a depth of approximately 20 cm in the GSR sediment samples. The generation of these holes may be related to biological activities, and the types of organisms suitable for survival in sediments of different strengths must also be different [69,70]. Many studies have measured the contents of Mn, Co, Ni, Cu and other elements in sediments at different depths [36,70,71], but have not simultaneously measured the physical and mechanical properties of sediments at different depths. It is not clear whether there is a corresponding relationship between the mechanical properties of sediments at different depths and the contents of Mn, Co, Ni, Cu and other elements. In future, we may be able to observe changes in the content of metal elements in sediments through changes in the mechanical properties of sediments. This requires the ability to measure the mechanical properties of the bottom sediments more quickly. Table 2 summarizes the advantages and disadvantages of different testing methods for assessing the mechanical properties of seabed sediments. In situ testing is undoubtedly a fast and reliable way to quickly assess the mechanical properties of shallow subsurface sediments. The development of in situ testing technology for the mechanical properties of seabed sediments can help to determine more accurately the mechanical properties of sediments, and to infer further results.

Table 2. Comparison of different test methods for the mechanical properties of sediments. Modified from reference [72].

Test Method	Test Parameters	Advantages	Disadvantages
Indoor test	Shear strength, cohesion, internal friction angle, etc.	Strong controllability and accurate test results	Sample preparation is troublesome; long test period
Cone penetration test	Penetration resistance and side friction resistance Pore water pressure	Wide range of applications and high measurement accuracy	Needs to cooperate with penetration device
Dynamic cone penetration test		Easy to test without additional power	Average measurement accuracy
Consumable dynamic penetrometers	Penetration resistance	Easy to use	Only suitable for shallow seas
Full flow penetrometers		High precision for measuring soft soil on the seabed	Probes need to be replaced for different sediment
Vane shear test	Shear strength	Can reflect small deformations of sediment	Average measurement accuracy

3. Mining Method

Deep-sea polymetallic nodule mining technology has undergone development in recent decades. In the 1960s, the United States first proposed the subsea towed bucket mining system, Japan proposed the continuous chain bucket mining system, and France proposed the shuttle ship mining system. Then, in the 1980s, France, Korea, Russia, USA, China, India, Germany, and Italy proposed the pipeline lift mining system, as shown in Figure 4a [73]. Based on considerations of economy, mining efficiency, technology, environmental impact, etc. [74], the mining method predominantly studied internationally has been the pipeline-lift mining system (Figure 4b) [57], which includes three main components: a seabed mining vehicle, a lifting pipeline and a surface mining vessel [75,76].

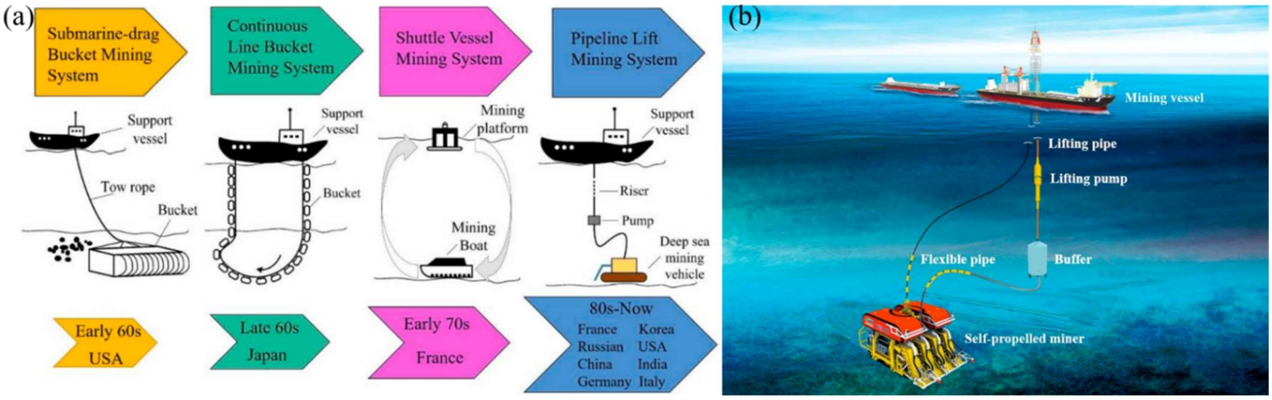

Figure 4. (**a**) the development of the deep-sea polymetallic nodule mining system [73]; (**b**) schematic diagram of the pipeline lifting deep-sea polymetallic nodule mining system [57].

Research on the seabed mining vehicle has mostly focused on how to move efficiently under the water, how better to collect nodules, and how to realize the positioning of a mining vehicle under disturbance. The problem of vehicle movement in the nodule area is very complex, involving a coupling process between mining trucks and sediment [77,78]. Putting aside the sealing and compression problems caused by water depth [79], from the perspective of sediments, the shallow surface sediments are very weak in the occurrence areas of deep-sea polymetallic nodules. They cannot provide a high bearing capacity, nor sufficient shear resistance for the advance of mining trucks [80,81]. In addition, the existence of nodules on the seabed surface adds a lot of uncertainty to sediment properties [81], which requires engineers to consider further problems. The deployment and recovery speed of deep-sea operation equipment, the movement speed of mining vehicles, and the collection speed of nodules are also worthy of discussion. Excessive speed of equipment layout and recovery can affect the accuracy of the sensor, cause a large disturbance when touching the bottom, and increase the risk of the mining vehicle falling into sediment. Insufficient speed will increase the time of distribution and recovery, and increase the economic cost. The high movement speed of the mining vehicle requires high collection efficiency, a good nodule-crushing effect [82] and a strong pipeline lifting capacity [83]. At the same time, the collection process will cause sediment disturbance, which means that an appropriate nodule-crushing mode, movement speed and collection speed will also be important factors affecting the environmental impact of mining [84,85].

The vertical pipeline lifting method is currently the main method of deep-sea polymetallic nodule mining research in various countries [83,86–90]. The nodules collected by the mining truck are transported to the surface of the sea by pipeline transportation. In the process of lifting polymetallic nodules, it is necessary to consider not only the magnitude of the pipeline lifting power [89,91], but also the concentration, size and viscosity of particles in the pipeline [92–95]. Mud that is too thick can easily block the pipeline, and mud that is too thin will affect the transmission efficiency. In addition, the amount of mud in the pipeline also affects the stability of the pipeline in water, and the external hydrodynamic effect has an impact on the stability of the pipeline and the whole mining system [95–99]. The research results of the above mining technology will eventually be verified through in situ tests, and the reliability of the technology will be repeatedly verified through mining simulation experiments. In recent years, various countries have gradually completed sea trials of self-developed deep-sea polymetallic nodule mining systems [86–90]. South Korea completed a sea test of its self-developed pipeline lifting device in 2016 [97], and China completed acceptance of the collection and lifting device of its self-developed polymetallic nodule mining system in the South China Sea in June 2021 [87].

Since 1970, deep-sea polymetallic nodule simulation mining experiments have often focused on exploration in developed countries [73]. Over time, nodule mining simulation experiments have come to focus on issues of environmental impact. In addition to some large-scale environmental perturbation experiments, mining perturbation experiments were carried out on seamounts in southwest England in 2016. The Remote Operated Vehicle (ROV) was used to simulate the mining situation to generate sediment disturbance, and then the movement of the resuspended sediment after the disturbance was observed by the in situ monitoring device [27]. In 2018, the Royal Netherlands Institute for Oceanography conducted a mining disturbance experiment at a water depth of 300 m. Changes in resuspension sediments were monitored over a range of 350 m [91]. Since 2017, Japan, the Netherlands, Belgium, Canada and other countries have successfully conducted sea trials and environmental assessments of deep-sea mining equipment, and the corresponding development of deep-sea mineral resources technology and equipment has gradually improved [92]. However, these small-scale mining experiments are limited in what they can simulate. The sediment perturbation produced by real commercial mining is thousands of times greater than that produced by current simulations, and it remains to be seen whether the existing research is representative of the real situation. In addition, the field has been developing for more than 40 years since the pipeline-lift mining method was proposed in the 1980s. There is no disruptive technological innovation in this mining method, and it is still the main research model around the world. Whether there will be more efficient, environmentally friendly and high-precision mining technology in the future remains to be further studied.

4. Influence of Sediment Migration on Ecological Environment

The ecological and environmental impacts of subsea polymetallic nodule mining are caused mainly by the seabed ore-collection process, the tailings discharge process, and the pollution generated by the sea surface platform and transport ships. In essence, impacts are created by the influence of the resuspended sediments disturbed during the migration process. Therefore, this paper discusses the environmental impact of deep-sea polymetallic nodule mining from the perspectives of sediment resuspension, resuspended sediment migration and diffusion, and resuspension sediment redeposition.

4.1. Disturbance of Seafloor Sediments

The seabed ore-collection process disturbs the shallow sediments of the seabed, and the resuspended sediments change the chemical properties of the water body, which eventually has an impact on the survival of organisms [100]; this is the most direct impact brought about by the mining of deep-sea polymetallic nodules.

Based on the results of the current simulated mining experiment in an area where polymetallic nodules are present, 5–15 cm sediments on the seabed surface were removed during mining [101]. This means that 2.5–5.5 t of sediment is disturbed and suspended for every 1t of polymetallic nodules mined during commercial exploitation [13]. The seabed ore-collecting process is the most direct way that biological activity is endangered. Seabed organisms are injured or even killed due to the rolling, suction and collision of ore-collecting equipment. In addition, mining activities also extract sediments and nodules from the seabed surface, changing the living environment of benthos [102], and causing some organisms which depend on nodules as fixed points to become homeless [20]. There are many organisms on the seabed. Some researchers have specifically established a relationship model between the abundance of seabed polymetallic nodules and the distribution of benthic communities, to explore the effects of seabed hydrodynamic and seawater chemical properties on the distribution of benthic organisms in the nodule areas [60,103]. The results show that the large seabed biodiversity in the CCZ is positively correlated with the volume and surface area of nodules. The abundance of macro-organisms is negatively correlated with the shear strength of shallow sediments [104]. Meanwhile, researchers from the University of Bremen in Germany also found that there are many pore channels at a depth of approximately 20 cm [14], which is speculated to be due to the influence of biological disturbance. This depth is directly damaged during the actual nodule-mining process, and its sediment properties change as mining progresses. It remains to be further analyzed whether the biological disturbance at this depth can be used as an indicator for the environmental impact assessment standard of deep-sea polymetallic nodule mining in future.

In addition to the direct effects of sediment disturbance, due to the resuspension of sediments, the benthos inhales many solid suspended particles during respiration, which is enough to affect the living state of organisms. Additionally, the degree of influence of particles with different sizes varies; the sediments with smaller particles have a greater impact [105]. By culturing organisms in water bodies with different concentrations of suspended solids, some studies found that even if organisms did not show a significant decline in activity, there was an obvious enrichment of suspended solids in their organs when dissecting their cadavers [106]. When metal ions are added to these solid suspended particles [107], it is conceivable that heavy metal ions would be enriched in organisms [108].

When mining activities are carried out, the oxygen consumption rate decreases significantly after removing surface sediments. As a result, oxygen penetrates into the sediment at a rate 10 times higher than before, thereby inhibiting denitrification and redox reactions [15] and changing the redox environment of superficial sediments. Manganese in the sediment has a higher solubility in the low-oxygen layer, and the clay minerals preferentially adsorb manganese ions in the oxidized environment [109]. This means that the mining of deep-sea polymetallic nodules and the disturbance of sediment may accelerate the dissolution of surrounding unmined polymetallic nodules, which may partly explain why the number of buried polymetallic nodules is very low.

4.2. Migration and Diffusion of Suspended Sediment

These resuspended sediments form a water disturbance zone approximately 50 m above the ground near the collector. Smaller particles diffuse with the bottom flow to form a plume with a particle concentration of 15–150 μg/L [60]. Initial studies suggested that it would take only a few days for the concentrations of these suspended solids to return to their original levels [7]. Because the hydrodynamic conditions in the deep sea are weaker than those at the mouth of the bay, the plume will last longer [110]. As shown by laboratory experiments, most of the sediment particles settle down in a very short period of time, but some other fine particles drift for a long distance with the bottom current before settling [111]. The temporal and spatial distribution of these resuspended particles has been investigated.

The results of Ocean Mining Inc's (OMI) deep-sea mining experiments in 1978 showed that the measured sediment thickness around the disturbance point was 1–2 cm, and there was a change in the concentration of suspended particles at a distance of 16 km from the disturbance point [112]. Based on the test results, a mathematical model was established to calculate and predict the movement trajectories of the particles, and the thickness of the re-deposited sediments was calculated to be approximately 1 mm in the area 400 m away from the disturbance zone. However, when the choice of the model differs, so do the movement trajectories of the particles. Based on the calculations of the Lagrangian model, fine particles at a distance of 200 m from the bottom can migrate as far as 192 km [113].

Although these findings are far from the previous calculation results, that does not rule out the possibility of their appearance in a real situation.

In addition, there are many influencing factors to be considered in the predictions of mathematical models. As shown in Figure 5a, the concentration distribution of suspended solids at the height of 1.5 m from the seabed was calculated in the model according to the settlement velocity of sediments obtained from indoor experimental tests [27]. The settling rate of resuspended particles seriously affects the moving distance of particles, and the gap between the sediment settling rate measured in the laboratory and that of the real settlement is not clear. The sediment particle sizes are different, the sedimentation rate is different, and according to their different material compositions, the influence of flocculation needs to be considered for some sediments. If the influence of hydrodynamic conditions is considered, even particles with the same particle size have different migration trajectories, as shown in Figure 5b [114].

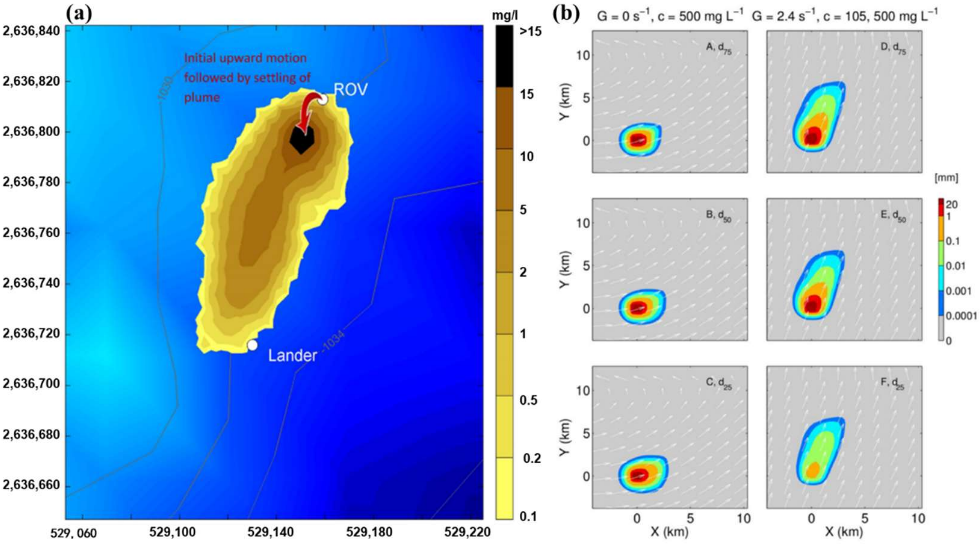

Figure 5. (**a**) The distribution of suspended solids at a height of 1.5 m from the seabed predicted by the model 13 min after disturbance [27]; (**b**) the area and thickness of resuspended particle sediments four days after particle disturbance for three different particle sizes under different simulated bottom-flow velocities [114].

In addition to sediment disturbance increasing the concentration of suspended solids in seawater, tailings discharge also increases the concentration of suspended solids in seawater [115]. The influence of metal ion concentration and nutrient concentration in the upper water body mainly comes from the discharge of tailings, but it is quickly diluted with the flow of the water body, and the influence of trace elements is lesser still [109,110]. Of course, there is a special impact index of tailings discharge, i.e., temperature. The seabed temperature at a water depth of 4000–6000 m is generally 1–2 °C, while the temperature of tailings generally exceeds 7 °C after calculation. The impact of this turbid water body discharge into seawater with a large temperature difference may be immeasurable [116]. In addition, changes in temperature and salinity are always inseparable. This change often leads to changes in the thermocline, especially in areas of shallow water depth [117]. Based on the above considerations, some researchers believe that the location of tailings discharge should be as deep as possible in the seabed, but this method may cause the suspended solids at the bottom to linger for longer. Therefore, through calculations, other scholars have suggested that the impact on the environment would be smallest at a position of approximately 500–800 m [118]. At present, the answer to this question is not conclusive.

The tailings discharge process mainly consists of the discharge of tailings slurry into seawater at different depths, an increase in the concentration of solid suspended particles and metal ions in water [115], and a change in the redox environment of water. In addition, due to the existence of solid suspended particles and metal ions, the concentration of dissolved oxygen in seawater is relatively reduced, and the redox environment of seawater changes. The latest research shows that, under the same biological conditions, changes in the redox environment seem to have a great impact on primary productivity in seawater, thus affecting this ecosystem [117].

4.3. Sedimentation of Suspended Sediment

The mining process and the discharge of tailings causes the suspension of many sediments in the water body. However, with the passage of time, the solid suspended particles produced by mining will eventually settle to the seabed surface, resulting in the redeposition of a layer of sediments on the seabed surface. It is estimated that the thickness of sediment redeposited in this layer during commercial mining is approximately 5–10 cm [67]. In the case of solid suspended particles in tailings, different from the suspended particles at the bottom of the seabed, the discharge of tailings generally continues to discharge into seawater at a fixed position. The continuous discharge causes the solid suspended particles to settle [113]. Particles of different sizes move differently during the settlement process, and the external environment affects the settlement of particles in tailings more than the solid suspended particles generated in the mining process.

Compared with the sediment before disturbance, the difference in porosity of heavy sediment is mainly concentrated in sediment less than 5 cm deep, and the change in porosity is approximately 0.65–0.8 [119]. Studies have shown that in the Peruvian basin, the upper 10 cm of sediment in the deep-sea polymetallic nodule area is an oxide layer, and there is a large change at the depth of 2 cm [110]. The area with rich oxygen content in the upper layer is conducive to the growth of nodules [42].

The rapidly settling mud will quickly cover the original seabed, change its morphological structure and affect vital benthic activity [115]. During the process of commercial mining, the offshore platform and transport ship continuously carry out the offshore operation, and the discharge into the ocean of excreta, domestic garbage and other waste generated by the ship's personnel is another impact that cannot be ignored [120]. In addition, it must be said that even if we are careful in the use of offshore platforms, plastic products will inevitably enter the ocean; these can be found even in the Mariana Trench, the deepest in the world [121]. There remain questions about the environmental impact these plastic products will have on the ocean. Regardless of the processes used, the impact mainly involves sediment, seawater and organisms, and the subject of focus is marine organisms. Shown in Figure 6a is a photo of the disturbance of seabed sediments, and the white rectangular box is a close-up of the scene where the benthic creatures are escaping; 6b is the appearance of the suspended sediment in seawater, and 6c is a photo of the resuspended sediment redeposited and then overlaid on the surrounding nodules.

Figure 6. Existence of polymetallic nodules on the seafloor before and after sediment disturbance. (**a**) is a photo of the disturbance of seabed sediments, and the white rectangular box is a close-up of the scene where the benthic creatures are escaping; (**b**) is the appearance of the suspended sediment in seawater, (**c**) is a photo of the resuspended sediment redeposited and then overlaid on the surrounding nodules.

Whether caused by the redeposition of resuspended particles or the deposition of mud discharged from tailings, the impact of rapid sediment deposition on the benthic activity is almost irreversible [122]. If the rapid deposition exceeds 5.4 cm, more than 50% of the benthos become completely immobile [123]. However, in general, the impact of tailings discharge on organisms is much smaller than the collection process [16]. Even if the mining disturbance is small-scale, it will take thousands of years to restore the stable chemical state of the surface sediments [15]. Of course, this estimate may be relatively conservative, and the recovery rate is different for different organisms [21]. For example, after the disturbance in the CCZ, the deep-sea nematodes in the disturbed area were investigated 26 years later, and the abundance of nematodes had still not returned to the original state [124]. Growth estimates suggest that microbially mediated biogeochemical functions need over 50 years to return to undisturbed levels [103]. Therefore, in any case, it is necessary to allow several decades for the area to recover to its level before the disturbance [61,125]. Moreover, this kind of deep-sea ecological environment restoration costs enormous amounts of money, and is likely to exceed its economic value [126].

5. Monitoring and Evaluation

5.1. Monitoring

Most of the initial monitoring focused on investigation, whether it was resource reserves, sediment properties, hydrodynamic conditions or biodiversity, and was carried out through voyage investigation. The initial investigation methods were very direct. Sediment and seawater samples were collected and taken back to the laboratory; the coverage and abundance of nodules were calculated, various parameters and indicators in seawater were tested, and microbial bodies were found in sediment and water. The data obtained by this direct sampling method are the most authentic, but in the ocean at a water depth of 4000–6000 m, it takes about 4 h to sample sediment or water, and the sampling efficiency is very low. With technological development, in order to improve the efficiency of investigation, submarine video images and acoustic reflection intensity can be obtained during hull navigation or Autonomous Underwater Vehicle (AUV) support by using the methods of submarine camera [127] and acoustic reflection inversion [128]. The above survey results were used to calculate the coverage of polymetallic nodules, the inversion of nodule abundance, hydrodynamic conditions, marine microorganisms and plankton communities. The digital assessment of resource reserves, hydrodynamic forces and biological community migration has greatly improved the work's efficiency, but it is undeniable that its accuracy needs to be improved.

According to findings on the impact of polymetallic nodule mining on the ecological environment, the focus of environmental monitoring is mostly aimed at sediment, seawater and biology. Whether obtained by indoor experiments or mining simulations, the results of the environmental impact are collected over a short time. The real impact of mining is determined over longer time series. A certain long-term in situ monitoring is required to truly understand the settlement process of resuspended sediments, and to evaluate the possible longer-term ecological environmental impact. The long-term in situ monitoring device currently used in the deep-sea environment is a submersible target system, which uses a floating ball and counterweight to fix the observation equipment at a certain height from the seabed to complete the monitoring [129]. The submersible target method can obtain good results for the monitoring of temperature, salinity, dissolved oxygen, nitrate, silicate, phosphate, chlorophyll a, water depth and other parameters, but it cannot be too close to the seabed, because the hydrodynamic data obtained at that range are easily affected by the counterweight, reducing their accuracy. In view of the environmental impact of polymetallic nodule mining, it is necessary to understand the changes in environmental parameters near the bottom layer. Therefore, an in situ observation device at the bottom of the sea may obtain better in situ observation results.

The monitoring equipment used by British scholars in the pilot production experiment in 2016 is shown in Figure 7a, including two sediment traps, the hydrodynamic condition of the upper part of a 35k-Acoustic Doppler Current Profiler (ADCP) measuring device, and four Optical Back Scattering (OBS) devices arranged at intervals of 0.5 m in the vertical direction to measure the concentration of suspended solids in seawater [27]. The equipment was generally in good condition. Except for the fact that two OBS devices failed, the other equipment worked normally. Although the equipment included an ADCP, it could not measure the hydrodynamic situation within 5m of the bottom layer due to the existence of a blind area. The in-situ observation device for the seabed boundary layer, developed by Chinese scholars, can achieve accurate measurement of near-bottom hydrodynamic force, as shown in Figure 7b, including ADCP measured upward and Acoustic Doppler Velocimetry (ADV) at 1m from the bottom, as well as a seabed camera and multi parameter turbidimeter [130]. This equipment has completed in situ observation at water depths of 680 m and 1400 m in the South China Sea. In addition to traditional monitoring methods, some scholars have proposed to observe the diffusion of sediments based on the performance differences of microorganisms with different solid suspended particle concentrations, so as to realize the monitoring of sediment plumes [131].

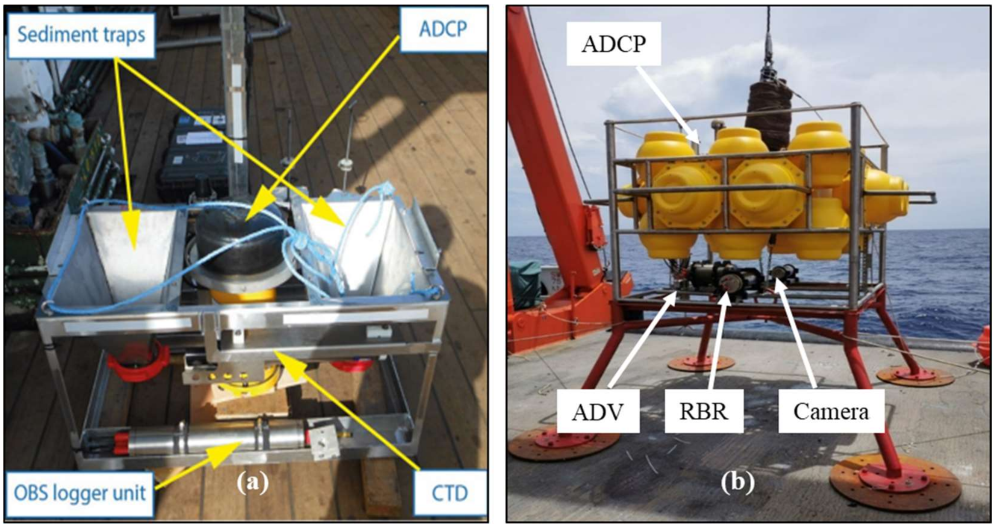

Figure 7. (**a**) The seabed in situ monitoring device used in the UK seabed disturbance experiment in 2016 [27]; (**b**) the in situ observation device used at the seabed boundary layer in the South China Sea in 2020 [130].

In any case, current monitoring technology continues to develop steadily. It is anticipated that more suitable monitoring methods and devices will be produced in the future, which will be more suitable for monitoring the ecological impact of deep-sea polymetallic nodule mining.

5.2. Evaluation

Based on the investigation of the long-term environmental baseline, the degree of environmental impact of deep-sea polymetallic nodules can be determined by comparing the changes caused by later mining activities, which is the basic idea of environmental impact assessment. However, as far as the investigation of the environmental baseline is concerned, its own variation range is large, varying with season, water depth, terrain, etc. [116,132]. Differential treatment of the environmental baseline in the process of environmental impact assessment is thus required. At present, the existing mining environmental impact assessment is mostly based on the problem structure framework model. Factors affecting the mining process include water depth at the extraction site, the depth of extracted sediment, and the processing return technique. Geologists and ecologists have included several environmental factors in their causal maps, including variables describing sediment characteristics and composition, water column chemistry, and hydrological parameters [133].

The causal relationship between polymetallic nodule mining and marine ecological environment systems is evaluated by giving weight to each influencing factor and introducing methods such as expert scoring, weight analysis and ecosystem service [19]. By analyzing the relationship between biodiversity and community composition at different locations in the CCZ, a research team can compare the weights of various influencing factors in order to make the evaluation results more accurate, but the final results may be different from those conventionally understood [58]. This method is also used for environmental impact assessment of mining. The land assessment adopts the statistical method to analyze the enrichment of heavy metal ions in the human body and to determine the state of human health. Finally, it evaluates the risk of metal mineral resources mining to human health [59]. The overall framework of this assessment method has never deviated from the problem structure framework model.

Scholars used a combination of the ocean circulation model and the Lagrange model to characterize the movements of resuspended particles by considering the physical and mechanical properties of sediments, deep seawater dynamics and particle migration trajectory, and then combined these factors with the impact assessment framework to evaluate the environmental impact of deep-sea mining [99]. The water depth considered in the model is 2000 m, there is a certain gap with the environment where the real water depth is 4000–6000 m, but there are no real in situ test data for the mining area that can be used to correct the model. However, it is undeniable that this evaluation model has made a big step toward quantitative evaluation. This method was also adopted in the environmental impact assessment report submitted by GSR [26], and at present constitutes the mainstream development direction of the future.

Recently, for the environmental impact assessment of seabed mining, four monitoring and identification standards formulated in Japan have been incorporated into the international standard [134–137]. In the future, these methods may also be incorporated into ISA environmental survey guidelines and used in commercial surveys around the world, and these standards will be used not only for seabed mining assessment, but also for environmental impact assessment and marine environmental surveys. Although relevant international standards for environmental impact assessment have been issued, further consideration should be given to the factors to consider, the weight of each factor in the impact, the final evaluation index, and how to conduct quantitative evaluation.

6. Conclusions and Prospects

6.1. Conclusions

1. Deep-sea polymetallic nodules mostly exist on the surface of the seabed at a water depth of 4000–6000 m, which may be related to the metallogenic model or the external environment. However, there is no doubt that the existence of polymetallic nodules in this form facilitates mining.
2. The relationships between micro-topography, sediment engineering geological properties and polymetallic nodule distribution characteristics have not yet been established, which means that the division of engineering geological units in nodule areas and the division of future mining areas lack an important theoretical basis.
3. Most of the mining equipment currently being developed is in the theoretical and experimental stages. In real commercial mining, the speed of equipment deployment and recycling, mobile working methods, etc., need to be standardized.
4. The existing research on the environmental impact of deep-sea polymetallic nodule mining mostly focuses on biological activity, and rarely considers the changes in sediment properties before and after disturbance. The analysis model for the spatiotemporal distribution characteristics of suspended solids in water is not yet mature, and there is a lack of in situ monitoring data to verify the model results. Current research has not been able to accurately predict the migration and distribution characteristics of resuspended sediments in seabed mining. Regarding the influence of seawater chemical properties and biological activities, the current research has not yet

been combined with the temporal and spatial distribution characteristics and the laws of resuspension sediments.

5. The current environmental impact assessment model of polymetallic nodule mining is still in the qualitative analysis stage, and its degree of impact cannot be assessed quantitatively.

6.2. Prospects

1. In the future, the engineering geological units of the deep-sea polymetallic nodule mining area needs to be refined. The basis of division mainly includes resource distribution, micro-topography and geological sediment engineering characteristics.
2. To better understand the spatiotemporal evolution of resuspended sediments from polymetallic nodule mining, reliable in situ observational techniques are essential. In the future, building a model will require a large amount of field monitoring data. At the same time, the calculation results of the model can also provide a basis for the deployment of monitoring equipment.
3. In the future, it is necessary to establish a relationship between sediment transport and diffusion, and the chemical properties and biological activities of seawater. Secondly, more attention should be paid to the changes in sediment properties after heavy deposition. Thereby, the environmental impact of deep-sea polymetallic nodule mining can be quantitatively evaluated based on the migration and diffusion of sediments.

Author Contributions: Conceptualization, Y.J. and Y.Q.; Methodology, Z.F.; Project administration, Y.J.; Supervision, Y.J. and F.C.; Writing—Original draft, Z.F.; Writing—Review and editing, Y.Q., Y.J., F.C., X.Z., N.Z. and B.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Hainan Research Institute of China Engineering Science and Technology Development Strategy (No. 21-HN-ZD-02), the National Key R & D Program of China (Grant No. 2018YFC0309200) and the National Natural Science Foundation of China (41831280, 42107157).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: This study used photos and samples provided by COMRA.

Conflicts of Interest: The authors declare no conflict of interest.

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