Marine Policy 149 (2023) 105505

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Thresholds in deep-seabed mining: A primer for their development

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ARTICLE INFO

Keywords:
Environmental management
Deep-seabed mining
International Seabed Authority
Management thresholds
Regulation
Precaution

ABSTRACT

The establishment of thresholds is integral to environmental management. This paper introduces the use of thresholds in the context of deep-seabed mining, a nascent industry for which an exploitation regime of regulations, standards and guidelines is still in the process of being developed, and for which the roles and values of thresholds have yet to be finalised. There are several options for integrating thresholds into the International Seabed Authority's regulatory regime, from being stipulated in regulations to being part of a mining contract, each option having its own advantages and disadvantages. Here we explore the range of ways that thresholds can be derived, set out the challenges in translating ecological and management data into thresholds, highlight factors for acceptance and operationalisation of thresholds in deep-seabed mining, and explain the necessity of refining thresholds as knowledge on impacts to features improves. Some comparable marine industries already use thresholds and these could potentially be used as starting points for the development of thresholds for deep-seabed mining. In order to be acceptable to the wide range of deep-seabed mining stakeholders, thresholds need to strike a balance among levels of harm acceptable by society, levels of environmental precaution justifiable by governments, scientific robustness, and operational practicality.

1. Introduction

A threshold is an amount, level, or limit of a measured indicator, created and used to help avoid unwanted change. In the context of environmental management, a threshold provides a limit that, when reached, suggests that a risk will – or is expected to - become harmful or unsafe, or provide an early warning of such an occurrence. In our daily lives, we come across numerous and varied thresholds imposed by local, national or international guidance or regulation, ranging from legally binding speed limits, the amount of fluoride regulated in drinking water, through to air pollution alerts. The aim of such thresholds is to balance possible benefits (e.g. efficient road travel times, increased oral health, benefits derived from energy production, agriculture and use of motor vehicles) with potential harms to individuals, society and the environment (e.g. risk of collision, risk of fluorosis and other health problems, health issues associated with pollution). Thresholds will be based on scientific evidence and societal values, both of which may change over time.

Thresholds are an inherent part of science-based environmental management [1,18,19] and many regulatory thresholds already exist to help manage levels of human impacts on terrestrial, freshwater and marine ecosystems. Often such thresholds have been implemented reactively following a dramatic change to an ecosystem, e.g., the introduction of restrictive catch quotas after the collapse of a fishery

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https://doi.org/10.1016/j.marpol.2023.105505
Received 15 July 2022; Received in revised form 22 December 2022; Accepted 22 January 2023
Available online 2 February 2023

[20]. For emerging industries such as deep-seabed mining (DSM), on the other hand, there is an opportunity to set initial thresholds for environmental impacts before the commencement of commercial activities.

Deep-seabed mining in the seabed beyond national jurisdiction (‘the Area’) is regulated by the International Seabed Authority (ISA), an organisation established under the 1982 United Nations Convention on the Law of the Sea [50] (UNCLOS) and the 1994 Agreement relating to the Implementation of Part XI of UNCLOS. The ISA is presently developing the legal framework for DSM in the form of its ‘Mining Code’, an umbrella term for all ISA rules, regulations, and procedures. The Mining Code sets out, inter alia, the legal responsibilities of contractors who hold exploration (and when they become available, exploitation) contracts with the ISA, states sponsoring these contracts, and the ISA itself, comprised at present of 167 Member States and the European Union. Key amongst these responsibilities is the obligation to protect the marine environment, as set out in articles 145, 192, and 194 of UNCLOS and reflected in the Mining Code.[1] Implementing this obligation requires finding agreement about the level of environmental harm that is acceptable and that which is not. In the DSM regulatory regime, thresholds will need to be established when operationalising environmental management plans, both for proactive management, by providing guidance about when to intervene in a timely manner to prevent undesirable ecosystem changes *before* serious harm occurs, and as hard limits which cannot be exceeded owing to the increasing risk of serious harm occurring.

This paper provides an introduction to how thresholds could be used in DSM environmental management, assessment, and regulation. Thresholds that have been tested and operationalised in similar industries are presented, and the potential for transferral to DSM scenarios is discussed. Barriers to adoption of thresholds are elaborated, and the options for positioning of thresholds within the ISA’s Mining Code are considered.

2. Thresholds: the basics

In environmental management, thresholds can be divided into two main categories – ecological and management thresholds [21].

2.1. Ecological thresholds

Ecological thresholds occur where a system experiences a qualitative internal or external change, often in an abrupt and discontinuous way [56]. Some of these changes may be reversible, but many are not, and ecological responses to reaching a threshold may vary. These ecological thresholds are sometimes termed ‘tipping points’ (e.g., [44], [55]), from which the system cannot on its own readily recover. Ecological thresholds are often the result of complex interactions among variables – naturally occurring (e.g., seasonality), and anthropogenic, both long-term (e.g., climate change, nutrient and pollutant input) and short-term (e.g., construction or maintenance operations) at a range of spatial scales, thereby making them difficult to predict and manage. In marine management, a now classic example for a system reaching a tipping point is the severe decline of the Newfoundland cod stocks and the associated shift in the ecosystem to an alternative state where lobsters dominated, leading to the closure of the Canadian cod fishing industry in 1992 [20]. While the identification of an ecological threshold may make the development of a meaningful management threshold more likely [19], in practice it can be fraught with a range of social, legal and political challenges [25] and the direct application of ecological thresholds to environmental management remains limited (e.g., [12], [51], [19]).

2.2. Management thresholds

Management thresholds can be found within environmental impact statements, environmental management and monitoring plans, technical publications, standards, guidelines, permit, licensing or contract conditions, and are set to prevent human pressures further impacting an ecosystem such that benefits or services cannot be delivered, or that benefits or services are reduced to a level judged to be unacceptable [21]. Thus, management thresholds are based on both scientific understanding as well as value judgements that involve political, economic, social and practical considerations.

Legally established terms such as ’serious harm’ or ’material change’ typically drive the need for establishing numeric management thresholds, and many have been internationally agreed upon (e.g., the International Maritime Organisation’s MARPOL Annex VI pollution thresholds or the UN Food and Agriculture Organization’s criteria for Vulnerable Marine Ecosystems[2]). Environmental management plans operationalise how environmental objectives and regulations will be met, mainly by ensuring that monitored indicators do not exceed predetermined thresholds [15].

Pragmatic management thresholds are easy to understand, based on readily measurable and cost-effective indicators that have a straightforward and well-understood link to an ecosystem response. For instance, 350 ppm CO_2 in our atmosphere has been widely adopted as a safe level to avoid a cascade of tipping points leading to global ecosystem change following [22]’s study. Where there is uncertainty or variability in the way an ecosystem might respond to pressure, as is expected in the deep sea, management thresholds and their implementation will need to display precaution and be open to adaptation. It is worth noting that multiple thresholds are often used for industry-wide licensing, for example in fisheries management strategies. The New Zealand Fisheries Harvest Strategy [38] provides one example of how multiple thresholds are used in practice. Targets are set (e.g., a stock size at/near biomass maximum sustainable yield (BMSY), or about 30% virgin biomass - dependent on stock productivity) and if the targets are met, then no management response is required. The next threshold level entails a soft limit, defined as stock size at 50% BMSY or 20% virgin biomass. If this soft limit is reached, it then triggers a requirement for a formal, time-constrained rebuilding and/or management plan. The final threshold level entails a hard limit (25% BMSY or 10% virgin biomass). The hard limit provides a biological reference point at which point closure should be considered for target fisheries.

It is envisaged that a similar set of staged thresholds would be useful for DSM, relating to minor harm which is deemed acceptable due to inclusion within a consenting envelope, to moderate harm where a management response and/or modification is required, and to serious harm (and risk of it), where mining activities would need to be significantly adjusted or stopped entirely. A submission regarding environmental threshold development was recently made to the ISA Council [27]. The submission highlights the stepped approach to environmental obligations under UNCLOS, related to effective protection, risk of serious harm, and the need to develop and implement measurable and science-based environmental thresholds linked to those obligations.

In data-limited situations, one may start with broader environmental goals and objectives that must be met, such as a percentage of area/habitat/ecosystem (etc.) that must remain protected, setting more specific thresholds as more indicator data become available over time. Threshold development is influenced by a wide range of factors that require expertise across several disciplines (Fig. 1).

[1] See e.g., ISA, *Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area*, ISBA/19/C/17, 22 July 2013, regulation 31–32.

[2] FAO, *International Guidelines for the Management of Deep-Sea Fisheries in the High Seas*, 2009, para. 42.

Box: terminology definitions used in this paper

Indicator: An agreed quantitative or qualitative value or measurable parameter that can be used to provide insight into the state of the environment, but also to measure effects of specific management measures (adapted from [49]).

Pressure / Stressor: Mechanism through which an activity has an effect on any part of an ecosystem. The nature of the pressure is determined by activity type, intensity and distribution.

Receptor: Part of the environment on which a pressure has an impact (e.g., organism, habitat).

Serious Harm: Any effect from activities in the Area on the Marine Environment which represents a significant adverse change in the Marine Environment determined according to the rules, regulations and procedures adopted by the International Seabed Authority on the basis of internationally recognized standards and practices informed by Best Available Scientific Evidence [26].

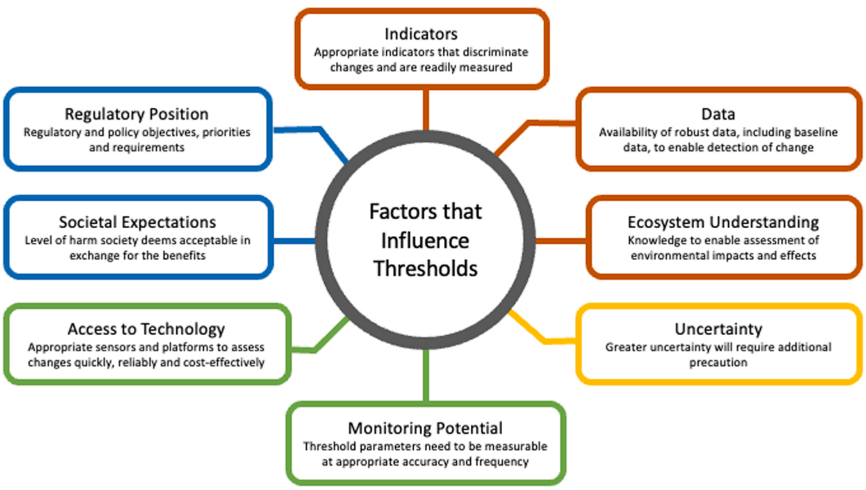

Fig. 1. The principal influences on threshold development and refinement. Note that these include a wide range of scientific, technical, legal and societal factors that will need to be considered for individual projects as well as cumulatively.
Factors are grouped as follows: green – ability to monitor, blue – licence to operate (social and legal), dark orange – ecological understanding and ability to detect changes, yellow – uncertainty, a factor that pertains to several other factors, including robustness of forecasting impacts.

3. Threshold development

Management thresholds are ideally set using robust baseline evidence, long-term monitoring, environmental understanding, and drawing upon best available practices. Where uncertainties exist (such as for a new industry that does not yet have a track record to draw from), a precautionary approach (described below) is needed, and success will depend on the ability to translate higher-level policy into what can be monitored operationally, e.g., monitoring techniques, size of a site, number of replicates and replicate sites, time required for monitoring, and monitoring frequency. Thresholds may need to be refined as more information becomes available, and this process will need to be fully documented, likely in the Environmental Management and Monitoring Plan. Thresholds also need to consider not just direct effects but also indirect and cumulative effects to the wider biological communities and/or habitats that may go unnoticed if monitoring is focused on direct interactions.

Management thresholds can be based on a variety of sources, including:

Source 1: Measurements of change to an indicator species or environmental condition that is known to reflect harmful impacts/effects more broadly:

a. Direct experimental measurements of harmful effects on a receptor (e.g., an experiment that investigates the level of suspended sediment concentration that leads to the death of 50% of organisms of interest). This could lead to species that act as 'a canary in a coal mine' for other species that are sensitive, albeit less so, to the pressure in question.
b. Experimental or field-based correlation between the receptor and a proxy that is simpler to measure (e.g., changes in the grain size distribution of sediments related to physical habitat stability).

Source 2: Use of the natural variability of a physical indicator under baseline conditions (e.g., the baseline range of suspended sediment concentrations found in the habitat prior to the proposed development occurring). This serves the purpose of a base reference against which the changes due to the implementation of a project are measured.

Source 3: Ecological analogues from another environment where pressure – receptor relationships are better known (e.g., initially using a threshold value of suspended sediment concentration that is known not to cause serious harm to a comparable receptor). The applicability of such analogues to the deep ocean would need to be scientifically considered prior to their operationalisation. If this involves an assessment of applicability through component or whole system testing, these thresholds may evolve from analogues (Source 3) into Source 1 thresholds.

Source 4: Numerical modelling of impacts and mortalities can provide the basis for thresholds that may otherwise be too resource-intensive or ethically challenging to gain through data acquisition (e.g., modelling of cetacean noise disturbance thresholds instead of a study exposing cetaceans to various noise levels).

Management thresholds derived from measurements (Source 1) can be developed in several ways. Firstly, they can be estimated from empirical data obtained from experiments. These data are ideally obtained in controlled settings (e.g., using Remotely Operated Vehicle experiments) using factorial experimental designs that investigate the potential impacts of a pressure or a suite of pressures. Such pressures may affect organisms at various levels of biological organisation, ranging from cellular and molecular to whole-individual responses that in turn can affect population dynamics. Physiological, biochemical and cellular responses often occur at lower pressure levels than whole-body responses and thus can serve as early warning indicators for serious harm (e.g., [2]). Ecotoxicological studies are useful in deriving such links, and they are widely used in informing the setting of thresholds for various pressures and biota. It should be noted that comprehensive databases of ecotoxicological studies relevant to the deep sea do not currently exist [23] owing to inherent difficulties in retrieving and keeping deep-sea organisms alive to perform the required experiments (e.g., [6]). Thresholds created for a regulatory setting need to take into account the variety of responses across the ecological community and ideally focus on the most sensitive species in a community, although these species may not yet be known or identified in the deep sea. A few studies have investigated deep-sea (benthic) responses to increased suspended sediments. To date, these laboratory-based studies have focused on coral and sponge responses in relation to drill-cutting exposures, bottom trawling sediment resuspension, and deep-seabed mining sediment plumes (e.g. [8], [16], [29], [30], [35], [36], [43], [47], [48], [52]).

Ecosystem models can aid in investigating how impacts at the species level may affect the whole biological community and may need to be considered in combination with the direct measurements. Duration of exposure to a pressure should also be considered in setting a threshold. For example, a prolonged exposure of increased suspended sediment concentration is known to lower response thresholds in various aquatic organisms [24,37]. In addition, the combination of increased levels of a pressure and the length of exposure duration to this pressure can be additive [37] or nonadditive [41] and is seldom linear.

The second type of management threshold developed from measurements are those focused on a measured relationship between two indicators. If there is a well-known relationship, then the threshold can focus on the indicator that is simpler and more reliable to measure. This approach has been used by the United Kingdom marine aggregates industry [13] with post-extraction thresholds for particle size distribution based on previous scientific investigations of the correlation of grain size distribution to the composition of faunal communities.

Setting management thresholds based on natural variability of (a suite of) physical variables (Source 2) is a commonly used approach for assessing abnormal and likely undesirable environmental conditions, e.g., in assessments of impacts of climate change (e.g., [46]). This approach assumes that the natural conditions and variability in which the organisms or communities occur represent boundaries for healthy, resilient systems, and is linked to the concept of an ecological niche, or the range of environmental conditions which allow survival and reproduction of organisms and communities. Operationalising this approach requires baseline data on the variability of the indicator in order to remain within its natural boundaries, but does not require specific information on the response of the receptor. Such thresholds may be set based on the range of variability, another statistical property (e.g., 95% confidence interval) or a multiple of the natural variability.

If insufficient site-specific data are available to start with, management thresholds may also be set using information or thresholds obtained elsewhere, such as from different industries or ecosystems (Source 3), based on different biological communities than those observed in the deep sea. This is a practical and quick method in the absence of empirical data or ecological knowledge. However, deep-sea systems are considered to respond to impacts very differently than shallow-water systems [7]. They may be more sensitive and have considerably longer recovery trajectories (e.g., [28], [53], [54]). Hence, such thresholds may represent a practical starting point, but need to be thoroughly tested in deep-sea ecosystems and adapted as appropriate, based on new or updated knowledge.

Management thresholds may also be developed from numerical estimation, informed by qualitative information, models or theory (Source 4, e.g., [5]. As these usually contain a number of assumptions, field-testing and further refinement of the threshold values should also be anticipated.

4. Iteration and precaution

Already adopted by the ISA in its exploration regulations,[3] and as included in the draft exploitation regulations, the precautionary approach calls for precaution that is proportionate to the uncertainty of the situation combined with the potential risk of harm. Where much remains unknown, the statistical power of baseline information is low, and where there is potential for lasting harm, precaution requires that a conservative approach is taken towards environmental management and assessment, with initial thresholds that are also conservative, but which may later be adjusted once more monitoring data and technical knowledge are available (at different scales).

Coupled with precaution is the concept of adaptive management. Starting with a conservative threshold(s), regulators can assess the actual operational impacts (typically through monitoring data provided by the operator), and if acceptable, incrementally relax the threshold value(s). However, such an approach is likely to require closely monitoring a range of indicators (not just the indicator associated with the threshold) at several representative test locations, using sufficient statistical power to detect minor impacts, i.e., effects that constitute less than ‘serious harm’. Once a representative range of impacts is characterised under normal operating conditions, then management thresholds can be refined to better reflect the range of impacts deemed to be acceptable and to maintain compliance. It is envisaged that regulators can impose, or contractors can propose refinements. If additional harms are discovered during monitoring, this updated information could lead to a tightening, rather than relaxing, of some threshold values.

As any human activity in the deep sea represents some level of disturbance, the management thresholds will be a statement of what represents ‘acceptable’ levels of harm caused by these activities. Defining an acceptable level of harm requires a multicriteria judgement ideally based on empirical data, ecological understanding of the impacts on temporal and spatial scales, and a valuation of the losses (to nature, the environment, and to humankind) in comparison to the benefits expected to be gained.

5. Thresholds operational in existing offshore industries

One of the methods listed above for development of thresholds includes the use of ecological analogues. Many environmental thresholds already exist for inshore and offshore activities, such as those for the oil and gas and dredging industries, which are operational and part of existing regulatory regimes. While existing industry thresholds may not be directly or immediately applicable to DSM, they may provide a reasonable starting point for the development of more specific thresholds. The table below (Table 1) progresses the initial exploration of industry thresholds developed in the ISA’s “Draft standard and guidelines for the environmental impact assessment process” (ISBA/27/C/4; [27]).

6. Application of existing thresholds to DSM

Operational thresholds that relate to the impacts expected from DSM activities are available in inshore and offshore industries (Table 1). For exploitation of polymetallic nodules, there are analogues with the impacts known to occur from dredging activities. While the industries above are generally shallow water (<50 m water depth), the oil and gas industry is increasingly operating commercially in waters deeper than 1500 m, with the deepest well drilled currently being at over 3400 m water depth. Although there are known differences in the responses of deep-water organisms to impacts, some thresholds listed in Table 1

[3] See e.g., ISA, *Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area*, ISBA/19/C/17, 22 July 2013, regulation 31(2).

Table 1
Examples of thresholds from offshore industries that may be relevant to development of deep-seabed mining thresholds.

Categories	Relevant DSM activity	Similar operational activities	Examples of known operationalised thresholds	Comments
Air Quality	Vessel operations	Other vessel and platform operations	Revised MARPOL Annex VI (limits air pollutants in exhaust gases; shipboard incineration, VOC emissions). IMO thresholds (Greenhouse Gas emissions)	Thresholds would be applicable to vessels used in DSM operations.
Noise	Vessel noise	Surface vessel operations	IMO thresholds (noise in the environment). National and regional disturbance thresholds for seabirds from marine energy installations.	Some similarity is likely, although DSM operations in the Area are likely to be in the order of 100–1000s of km from seabird breeding grounds.
	Collector vehicle and riser operation	Dragheads and risers used in aggregates dredging operations; stationary drill risers used in oil and gas	Quantitative disturbance and injury thresholds for marine mammals from impulsive and non-impulsive noise (e.g., Temporary Threshold Shift (TTS) onset at 178 dB re 1μPa^{2}s for high frequency marine mammals (non-impulsive noise) and 170 dB re 1μPa^{2}s) weighted for impulsive noise [45]. The authors are unaware of any thresholds for deep-sea benthic species from impulsive or non-impulsive noise.	As thresholds are present for the full auditory range of marine mammals, thresholds should translate for use in DSM operations.
	Installation/decommissioning activities (piling/explosives)	Offshore wind farm installation		Piling for offshore wind is louder, but shorter lived, compared to DSM operations. This may affect suitability of thresholds.
Light	Vessel operations	All marine activities requiring light (e.g., shipping, oil and gas platforms)	There are no international threshold levels for light pollution for biota living either in the deep sea or on the sea surface. Typically, operations aim to reduce the use of light to the extent possible, while allowing for safe operations, and/or use low-level/red filtered lights to limit interference to marine life.	Thresholds in existence for vessels/ platforms and deep water ROV/AUV operations would be applicable to DSM, e.g.,[33],[40].
	Equipment transiting through the water column	Seafloor vehicles, ROV, AUV descents and ascents		
	Benthic Collector/Mining operations, monitoring and maintenance with ROV/AUV	Collector operations, monitoring, maintenance of subsea operations		
Water Quality	Vessel operations	Normal ship discharges (e.g., sewage treatment, macerated food waste)	IMO thresholds (London Convention/ London Protocol measures to prevent pollution by dumping of wastes).	Thresholds in existence for vessels/ platforms should be applicable to DSM.
	Sediment plume dispersal from return water discharge or from mining operations – related to spreading of contaminants/metals	All applicable marine activities	Australian and New Zealand water quality guidelines (trigger values for concentrations of metals and toxicants allowable at alternative levels of protection (% species protected). [3], [4].	These thresholds have been applied to marine activities, such as dredging. The guidelines were used to define the "mixing zone boundary" of the sediment plume for the Solwara 1 project in Papua New Guinea. [11] Applicability of these guidelines to deep-sea species will require further research.
	Sediment plume dispersal related to sediment/turbidity	Shallow water sand mining	For defined distances, a threshold level of 10 mg/L is set to protect demersal fish [17].	Similar activities are being regulated, though involving different soil/sediment types from those of nodule fields
		Navigational dredging (sediment plume from draghead)	For the Øresund link project (Sweden/ Denmark), the spill budget of suspended sediment flowing outside the project boundaries was agreed and monitored in real time. If exceedances were imminent, contractor mitigated by either reducing operation rate or by moving to another dredging area, where budget was still available [31]. Øresund link – turbidity monitoring used contiguous thresholds in area of impact (sedimentation concentrations above a threshold in 2 fish migration areas, water visibility in a swan grazing area and for bathing beaches, sedimentation limits in areas with mussel beds) [31].	Continual plume creation as per DSM requires monitoring for spatial exceedances; While the Øresund link work occurred in shallow water and faster current regimes, similar sediment types were involved.
		Construction dredging works (sediment plume from draghead)	Wheatstone LNG Project, Australia – license included tiered turbidity trigger levels to ensure protection for corals, seagrass and macroalgae. Plume density monitored through the day using satellite-telemetered water quality instruments [9].	Continual plume creation as per DSM requires monitoring for spatial exceedances; similar sediment types involved at least in part. However, Wheatstone work occurred in shallow water.
		Navigation channel dredging works	Vale iron ore facility, Malaysia. Sediment spill threshold levels defined – 1) a daily "spike" exceedance, 2) 3 day running averages and 3) 7 or 14 day running averages. Level 1 required no immediate	Continual plume creation as per DSM requires monitoring for spatial exceedances; similar sediment types involved. However, Vale operations occurred in

(continued on next page)

Table 1 (*continued*)

Categories	Relevant DSM activity	Similar operational activities	Examples of known operationalised thresholds	Comments
			action. Level 2 required investigation of exceedance and mitigation. Level 3 required immediate actions [42].	shallow water and higher current conditions than expected in the deep ocean.
		Sediment discharge/ disturbance activities (contaminants)	Thresholds exist for contaminants (sediment quality guideline values (SQGVs)). In Spain, there are 3 action levels for dumping at sea, according to concentrations of metal contaminants. Level C for any metal means that those sediments are highly contaminated, and cannot be dumped at sea [10,34].	These thresholds may be applicable to DSM, however, to establish SQGVs for disturbing deep sea sediments, comprehensive baseline studies would be needed.
Spread of invasive species	Vessel operations	Maritime industries covered by IMO	IMO's 2019 Ballast Water convention and IMO's 2011 biofouling guidelines.	Applicable to surface vessels in DSM operations.
Sedimentation (deposition thickness)	Sediment plume deposition	Oil and gas industry	Thresholds for sediment deposition: 0–1 mm is negligible impact, 1–3 mm is low impact, 3–10 mm is significant impact, >10 mm is considerable impact [39].	Similar types of sediment deposition, hence potentially applicable to DSM, though sensitivities may be different.
	Sediment plume deposition	Oil and gas drilling	Sediment coverage should be <10 mm in total to avoid considerable exposure for cold water corals [14].	Potentially applicable to DSM, though sensitivities may be different.

could potentially be considered for transferral and adaptation to a deep-sea context.

Thresholds from other offshore industries are potentially comparable enough to provide a starting point for the development of thresholds for deep-seabed mining for a similar impact, although they may require additional precaution to account for unknown differences in the responses of the ecosystems. These thresholds are often detailed, for example, considering plume parameters for sedimentation and contaminants. They have all been proven to be measurable, and many of such impacts can be monitored in real time, with enforcement pathways available if transgressions occur. Both international and site-based thresholds have been considered and made operational.

7. Integration of thresholds, UNCLOS and the Mining Code

To contribute to the environmental management of DSM, thresholds need to be placed within a regulatory regime. It is envisaged that in the ISA's mining regime, thresholds would function to help in achieving effective protection for the marine environment, as required by Article 145 of UNCLOS, and furthermore, should be seen as part of an early warning system that alerts the regulator and contractor before serious harm is caused, to allow for a management response aimed at avoiding serious harm. Conceivably, this early warning threshold system would require at least two regulatory thresholds: first a threshold that indicates movement away from the level of acceptable impact/harm, and second a threshold for risk of serious harm occurring. Further non-regulatory thresholds may also be chosen between the first and second regulatory thresholds to enable a gradation of more finely nuanced management responses. Setting precautionary thresholds for a given DSM operation that provide adequate protection of the environment, but at the same time include sufficient flexibility in the selection of practical technology and techniques will not be an easy task, and efforts may not strike the right balance in the first iterations of defining such thresholds.

Pursuant to UNCLOS and the Mining Code, the threat of serious environmental harm may be used to trigger regulatory processes such as rejection of, or a requirement to amend, an application for a mining contract,[4] emergency orders, which may include orders for the suspension or adjustment of operations,[5] and potentially compliance notices.[6] Whether there may also be liability issues associated with proven serious harm (i.e. where there are clear grounds for believing that serious harm is likely to occur or has occurred as a result of a DSM activity) is legally plausible. However, it is not defined whether the liability threshold for compensable damage would actually sit at "serious harm" or perhaps below [32].[7]

While it is envisaged that the requirement for thresholds would be set out in the future Exploitation Regulations, and possibly also the current Exploration Regulations, the specific threshold values could be specified in any number of documents. Table 2 summarises the advantages and disadvantages of several options.

8. Discussion and conclusions

Thresholds are likely to be inherently part of the operationalisation of environmental management plans for deep-seabed mining. Development of fair and effective thresholds will require wide-ranging acceptance from scientific, legal, management, and political perspectives. With the current levels of uncertainty associated with the commencement of DSM exploitation operations, precautionary thresholds adapted from comparative industries may represent a good initial approach. However, undesirable ecosystem changes will need to be detectable *before* serious harm occurs, to trigger initial management actions (such as more detailed or more frequent monitoring and alteration of mining practices). Hard limits that cannot be exceeded, owing to the increasing risk of serious harm occurring, will also need to be established.

It is expected that threshold effectiveness will increase over time. For thresholds to be effective in the environmental management of deep-seabed mining, we suggest the following should be met:

[4] UNCLOS, Articles 162(2)(x), 165(2)(l); ISA, *Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area*, ISBA/19/C/17, 22 July 2013, regulations 4(3), 21(6), 31(4).

[5] UNCLOS, Articles 162(2)(w), 165(2)(k), ISA, Regulations *on Prospecting and Exploration for Polymetallic Nodules in the Area*, ISBA/19/C/17, 22 July 2013, regulation 33.

[6] UNCLOS, Article 139, annex III article 22; ISA, *Draft Regulations on Exploitation of Mineral Resources in the Area*, ISBA/25/C/WP.1, 22 March 2019, draft regulation 4(5).

[7] ISA, *Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area*, ISBA/19/C/17, 22 July 2013, regulation 30, annex IV section 16.

Table 2
Options for the placement of thresholds within the ISA's regulatory regime and potential consequences thereof.

Modality	Advantages of the potential location	Disadvantages of the potential location
Regulations	1. Consistency across all mining contract areas 2. Transparency (publicly accessible) 3. Subject to public consultation during the development of the Exploitation Regulations	1. Difficult for changes to be made 2. Would not correspond with where thresholds sit for many other industries 3. Assumes thresholds for exploitation will be applicable across all mineral types and all mining contract areas, which may not be appropriate 4. Review of regulations, and hence the thresholds, is unlikely to be frequent or regular
Regional Environmental Management Plans (REMP)	1. Would be region and resource-specific 2. Consistency across mining contract areas within a region 3. Transparency (publicly accessible) 4. Could be subject to public consultation as part of REMP consultations 5. Subject to regular review as part of REMP review process	1. Non-binding unless compliance is required through the exploitation contract 2. A process of regular review for REMPs is not yet established, and there may need to be a grace period allowed for contract conditions to align with changes to the REMP
Standards	1. Transparency (publicly accessible) 2. Standards should be regularly reviewed	1. Unclear whether the process for making changes would be cumbersome 2. A process of regular review for Standards is not yet established
Guidelines	1. Transparency (publicly accessible) 2. Amendments might be relatively straightforward to implement in response to updated scientific data and knowledge 3. Greater flexibility to put forward a variety of good practices	1. Likely to be non-binding (unless specifically referenced as binding in the contracts) 2. Usually associated with voluntary monitoring and compliance
Contractual terms	1. Site-specific 2. Operational limits/ thresholds described in the EIS/EMMP (see below) will likely be linked with the contract	1. Less transparent unless contract conditions (or at least the thresholds) are stipulated to be made public in the exploitation regulations or through contract conditions. 2. May not be subject to review during the term of a contract, unless there is a specific contract condition that requires such a review. 3. May risk inconsistency – and therefore incomparability – between contracts in the same region, issued over time
EIA documentation (EIS and/or EMMP)	1. Site-Specific 2. Transparency (likely publicly accessible) 3. Likely subject to public consultation as part of the broader contract consultation process 4. Environmental performance is a strong component of the review/monitoring sections in the draft Exploitation Regulations and regular reviews (at least of the EMMP) are expected	1. May risk inconsistency – and therefore incomparability - between contracts in the same region, conducted over time

1) A threshold should be SMART (Specific, Measurable, Achievable, Relevant, Time-bound), with particular emphasis on the need to be measurable in a timely fashion
2) A threshold should be clearly presented and understandable, with explanation of why it is appropriate for deep-seabed mining regulation
3) A threshold should allow the detection of change and it should be set within a monitoring regime entailing sufficient statistical power to reliably separate acceptable values from unacceptable ones
4) A threshold should relate directly to management actions and environmental goals/objectives
5) A threshold should incorporate appropriate precaution and the ability for incremental improvement
6) The regulatory framework should require that thresholds be established, and the regulatory framework should provide for compliance/enforcement measures
7) The process for threshold development should be inclusive, consulting stakeholders with a broad range of expertise, experiences, and values.

Each of these requirements comes with its own challenges. While an initial threshold could aim to meet some of the above requirements (e.g., being 'specific', 'relevant' and 'time-bound'), realising others (e.g., 'measurable' and 'achievable') will rely on increasing understanding gained from baseline and monitoring surveys before and during operations. In terms of the need for scientific rigour, some industry thresholds involve statistical testing while others rely on expert judgement. In an environment such as the deep sea, where information is relatively limited, it is possible that some thresholds need to be refined over time from a starting point that is mostly informed by expert judgement, analogues or modelling, but which will move towards greater scientific rigour as more information is gathered. Regardless of how they are first established, DSM thresholds should be open to further refinement. Such adaptation may be active, through deliberate experimentation, or reactive, through comprehensive monitoring programmes. Whichever approach (or mix of approaches) is taken, the basis for any DSM threshold needs to be clearly and transparently documented, including the approach used, the indicators on which it is based, assumptions and data sources, monitoring regime to test its efficacy, the statistical power (i.e., confidence) of that regime, and the process for testing and refining it further.

While a level of precaution will need to be inherent in their development and management, thresholds also need to be operational. Understanding and realising that balance will be a central challenge, and initially linking thresholds to wider-scale environmental goals and objectives may be one way of tackling it, with thresholds being set against more specific targets as more indicator data become available. Component and whole system testing as well as the ramp-up stages of commercial operations would allow not only more detailed understanding of these operational indicators and relationships to the requirements of the Mining Code, but also aid in evaluation of methods and values used by comparable industries for adapted transferral into the deep-seabed mining regime.

The present ISA negotiations on the development of the exploitation regulations offer a valuable opportunity to ensure the use of thresholds in the responsible management of DSM. There are several options for integrating thresholds into the International Seabed Authority's regulatory regime, from being stipulated in regulations to being part of a mining contract; each option having its own advantages and disadvantages. To adequately protect the marine environment, these thresholds will need to be scientifically justifiable, appropriately precautionary and adaptive, and may be developed using existing experience from comparable industries, through a sufficiently inclusive process to represent a breadth of expertise, experience and societal values.

CRediT authorship contribution statement

B. Hitchin: Resources, Conceptualization, Writing - original draft, Writing - review & editing. **S. Smith:** Resources, Writing - original draft, Writing - review & editing. **K. Kröger:** Conceptualization, Project administration, Writing - review & editing. **DOB Jones:** Conceptualization, Writing - review & editing. **A. Jaeckel:** Resources, Writing – review & editing. **NC Mestre:** Resources, Writing – review & editing. **J. Ardron:** Resources, Writing – review & editing. **E. Escobar:** Resources, Writing – review & editing. **J. van der Grient:** Resources, Writing – review & editing. **T. Amaro:** Resources, Writing – review & editing.

Disclosure

SS works with Global Sea Mineral Resources nv, an International Seabed Authority Contractor. NOC have a contract with Nauru Ocean Resources Inc., an International Seabed Authority Contractor, for environmental work. All authors declare this work is their own and represents their own individual views.

Data Availability

No data was used for the research described in the article.

Acknowledgements

Funding: This work was supported by the UK Natural Environment Research Council (NERC) through the Seabed Mining And Resilience To EXperimental impact (SMARTEX) project (Grant Reference NE/T003537/1). The funders had no role in conceptualisation, analysis or reporting of results. This work was also supported by the Australian Research Council's DECRA scheme (grant number DE190101081), the German Federal Environment Agency (project FKZ 3718252200) and Fundaç ão para a Ciência e a Tecnologia (FCT), Portugal through the projects BiDiRisk (PTDC/CTA-AMB/2894/2021) and DEEP REST (DivRestore/0009/2020) and the grants CEECIND005262017 and UID/00350/2020CIMA.

The authors would like to thank MarineSpace Ltd for providing their expertise in management of marine aggregates and the two anonymous reviewers for their thoughtful reviews which helped us in improving the quality of the manuscript.

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